OCEANOBS'19: AN OCEAN OF OPPORTUNITY. VOLUME III

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OCEANOBS'19: AN OCEAN OF OPPORTUNITY.
VOLUME III

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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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MINI REVIEW
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Lessons Learned From the United States Ocean Observatories Initiative

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The Ocean Observatories Initiative (OOI) is a United States National Science Foundation-funded major research facility that provides continuous observations of the ocean and seafloor from coastal and open ocean locations in the Atlantic and Pacific. Multiple cycles of OOI infrastructure deployment, recovery, and refurbishment have occurred since operations began in 2014. This heterogeneous ocean observing infrastructure with multidisciplinary sampling in important but challenging locations has provided new scientific and engineering insights into the operation of a sustained ocean observing system. This paper summarizes the challenges, successes, and failures experienced to date and shares recommendations on best practices that will be of benefit to the global ocean observing community.

Keywords: ocean observing, lessons learned, technology development, best practices, equipment testing

INTRODUCTION

The Ocean Observatories Initiative (OOI)[1] is a United States (US) National Science Foundation (NSF) major research facility and is the NSF's contribution to the Global Ocean Observing System. It provides continuous observations spanning the seafloor, overlying ocean, and atmosphere of coastal and open ocean locations in the Atlantic and Pacific (Smith et al., 2018). Data collected, maintained, and disseminated by the OOI address significant scientific challenges such as coupling between the atmosphere and ocean (Chen et al., 2018; Ogle et al., 2018), coastal ocean dynamics (Zhang and Gawarkiewicz, 2015; Henderikx Freitas et al., 2018), climate and ecosystem health (Barth et al., 2018; Femke et al., 2018), the global carbon cycle (Palevsky and Nicholson, 2018), plate-scale seismicity (Nooner and Chadwick, 2016; Wilcock et al., 2016), and linkages between seafloor volcanism and life (Philip et al., 2016; Spietz et al., 2018). More information about the background and science objectives of the OOI can be found in Trowbridge et al. (this issue).

The OOI comprises a network of technologically advanced cabled and uncabled platforms that includes surface and subsurface moorings, moored profilers, seafloor nodes, and autonomous vehicles (**Figure 1**) with sensors that measure physical, chemical, geological, and biological properties at scales of centimeters to kilometers and microseconds to decades. The OOI was designed to evolve through incorporation of new technologies as well as novel research and educational proposals from the global community.

[1]https://oceanobservatories.org/

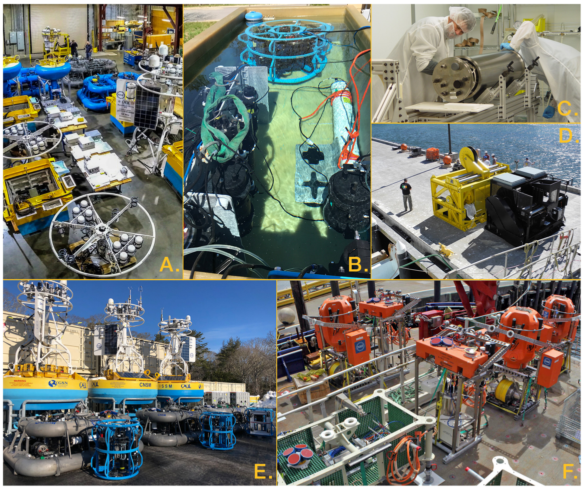

FIGURE 1 | Ocean Observatories Initiative (OOI) Equipment and Testing centers. **(A)** OSU Ocean Observing Center high bay; **(B)** Coastal mooring instruments being tested for operation in saltwater at WHOI; **(C)** Cabled Array Platform Interface Controller being assembled in clean room; **(D)** OOI Medium and Heavy Lift Winches staged for installation on R/V Thomas G. Thompson; **(E)** Coastal Moorings await deployment; **(F)** Cabled Array Secondary Nodes, Shallow Profilers, and Platform Interface Assemblies mobilized on aft deck of R/V Sikuliaq. Credits: Craig Risien, OSU **(A)**; Sheri White, WHOI **(B)**; Eric McRae, UW **(C)**; Geoffrey Cram, UW **(D)**; Kristopher Newhall, WHOI **(E)**; Deborah Kelley, UW **(F)**.

The OOI Cyberinfrastructure makes these data freely available online to a global audience, providing as much data as possible in real- and near-real-time. Data are available in multiple forms, including raw data received from sensors prior to quality control through processed data products. During the third quarter of 2018, the OOI data portal[2] received 6,100 visits from 56 countries with a total data download of 45.64 GB. The machine-to-machine interface and raw data archive were also heavily utilized and allow for the transfer of larger files, such as HD video files and hydrophone audio files. Over 31 million successful requests were made to the machine-to-machine interface totaling 573 GB of data transferred. The raw data archive received 5,000 visits from 29 countries for a total of 14.56 TB of data transferred.

Multiple cycles of OOI infrastructure deployment, recovery, and refurbishment have now occurred. The OOI facility, which includes over 800 instruments and almost 3,000 data streams, provides multidisciplinary sampling in important but challenging environments and can provide new scientific and engineering insights into the operation of sustained ocean observing systems. As noted in Lindstrom (2018), the OOI, through construction and transition to operations, has provided a pathway for the development of observatory infrastructure and testing of technology readiness that can be utilized by observatories across the globe.

This paper summarizes some key challenges, successes, and lessons learned to date by the OOI and shares recommendations on best practices and considerations that may benefit the global ocean observing community.

[2]https://ooinet.oceanobservatories.org

LESSONS LEARNED WORKSHOP

Representatives from organizations involved in OOI implementation, operation, and program management met 2–4 May 2018 to discuss important lessons learned since operations began in 2014. Topics discussed included field verification sampling and data quality control, platform communication and tracking, technology refresh priorities, cables and connectors, design issues and ease of use, profilers, and cruise operations. Lessons and details discussed during the workshop provide the basis for this paper focused on observing technology development, testing, and operation.

PRE-DEPLOYMENT TESTING

Prior to deployment, instruments and platforms undergo rigorous testing, separately and as integrated units, to ensure successful operation (**Figure 1**). Pre-deployment instrument testing occurs after manufacturer calibration and includes physical inspection, power-on test, operation and burn-in in saltwater, and integration with the platform for all OOI systems. Data transmissions and communications are tested during the burn-in phase. Cabled Array components are additionally subjected to in-house pressure testing, electrical characterization, electrical isolation testing, and corrosion mitigation. Disassembly after testing is minimized prior to deployment. Whenever possible, similar instrument models are tested together, and consistent testing procedures are conducted for the same instruments across program facilities.

Improvements have been made to enhance documentation and consistency in testing procedures and checklists. These documents are available through the OOI website[3]. Additionally, improvements such as testing instrumentation and electronics housings in saltwater tanks to find potential ground faults in sub-assemblies (**Figure 1B**) have enhanced testing capability and improved reliability.

The addition of non-core or Principal Investigator (PI)-based instruments – instruments that were not part of the OOI Final Network Design[4] – brings new challenges. Researchers interested in adding instrumentation must work with OOI operators during the proposal process to conduct a technical feasibility assessment. This is necessary to ensure new platforms and instruments operate correctly when interfaced with OOI infrastructure and do not cause adverse effects on existing infrastructure. PI-supplied platforms and instruments must be delivered months prior to deployment to ensure sufficient time for integration and testing. Examples of PI-added instruments and platforms are in Section "Community Engagement."

[3]https://alfresco.oceanobservatories.org

[4]https://oceanobservatories.org/planning-history/final-network-design/

DEPLOYMENTS

Several lessons have been learned and improvements made in the deployment of specific infrastructure elements. Given the large size and quantity of equipment to be deployed on a given maintenance cruise (e.g., buoys, seafloor nodes, anchors, cables, profilers, gliders, instruments), deck space is a precious commodity; not all vessels can accommodate the OOI's cruise requirements.

Though deck space is limited, commonly there are available berths on OOI cruises that provide opportunities for students and other researchers to participate and conduct ancillary scientific activities. A clear process and guidelines are being developed to maximize such opportunities with broad user community engagement[5].

Improved coordination between the OOI, ship operators, and schedulers is needed to ensure that proper equipment can be installed if necessary to meet the operational requirements of the OOI. For example, the large moorings deployed on the Cabled Array required construction of two different, purpose-built, portable deck winches (8,000 and 25,000 lb full-drum pull) to safely handle the various mooring needs (**Figure 1D**). Ships must be able to accommodate the installation and operation of both winches for deployment and recovery of the Shallow Profiler Moorings.

Improving ease of use and transport of equipment is a priority and should be considered during technology refresh and refurbishment. Minor design improvements have been made to infrastructure to ensure safer deployment and recovery without altering the overall function. For example, the Coastal Profiler Mooring anchor design was modified to include a top plate with multiple bales for recovery by ROV and safer handling on deck (**Figures 2C,D**).

[5] https://oceanobservatories.org/information-for-researchers/

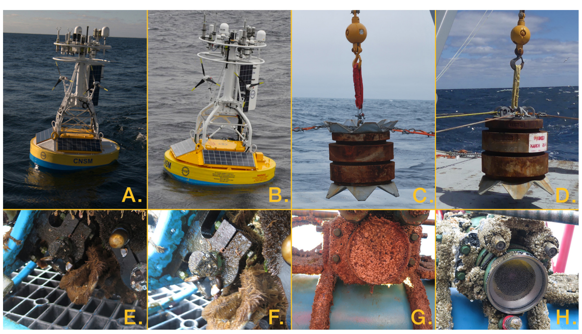

FIGURE 2 | Examples of equipment modifications. Enhancements in Surface Buoy tower modifications from **(A,B)** include, rearranging halo components to move telemetry sensors down and wind sensors up; replacing flat tower legs with tubular legs to prevent torsion; widening of vane to improve ability of buoy to point toward the wind. Updates to the Coastal Profiler Mooring Anchor design **(C,D)** to include top plate with multiple bales for recovery by ROV and safer handling on deck. Pre- and Post-biofouling mitigation photos on oxygen optodes **(E,F)** and cameras **(G,H)** on the Endurance Array. Credits: **(A–D)** WHOI; **(E,H)** OSU.

Ocean Observatories Initiative Coastal Arrays (uncabled Endurance and Pioneer) are serviced biannually, while the Global Arrays (Irminger Sea, Station Papa and, previously, Southern Ocean and Argentine Basin) and the Cabled Array (including cabled Endurance Array) are serviced annually. In addition to the biannual maintenance schedule, some coastal assets require quarterly servicing. These include Coastal Surface Piercing Profilers (CSPP) due to battery limitations and Coastal Gliders. As these are both relatively small pieces of infrastructure, cruises are conducted via a small ship with an A-frame.

Cruises must be timed to optimal weather conditions and to ensure sufficient intervals between cruises for refurbishment and recalibration of equipment. For example, northern hemisphere Global cruises (Irminger Sea and Station Papa) must occur between June-August for optimal wind and wave conditions; southern hemisphere (Argentine Basin and Southern Ocean) conditions are best in December-February. Equipment must be shipped 2 months before cruises in the southern hemisphere to arrive in time. Coastal cruises must be spaced as close to 6 months apart as possible (Spring and Fall time periods) to allow sufficient time for refurbishment and recalibration of equipment before redeployment.

During cruises, flexibility is critical because of the weather-dependence of many activities. For example, each type of mooring has a certain maximum sea state it can be deployed or recovered in, such as 3-m significant wave height and 10 m/s winds from typical Global Class ships. Looking at four cruises to the Southern Ocean Array between February 2015–December 2017, even though these cruises were scheduled during the ideal climatological window, at least a third of the days during each cruise had weather sufficiently bad that moorings were not able to be deployed. During the 2017 cruise, two thirds of the days had sufficiently bad weather to prevent operations.

Optimal service frequencies of components based on historical experience with similar technologies are being reviewed and updated continually after each turn cruise. For uncabled moorings, the degradation of mooring components, biofouling of instruments, and depletion of batteries are the main drivers of the maintenance schedule. Annual inspections of deployed junction boxes on the Cabled Array confirmed they may only require refurbishment on a 5-year timeframe, assuming no refresh is needed to accommodate new PI-supplied instruments. In some cases, plans for repeated use of specific infrastructure components were found untenable based on inspection of recovered gear, e.g., cuts/breaks in wire rope jacketing and failure of stretch hoses.

FIELD VERIFICATION

Field verification sampling is an important component of all OOI cruises to determine whether data coming from sensors are reliable when first deployed. This is done using a variety of sensors and sampling, including shipboard meteorological, upper ocean and flow-through systems, CTD casts, bottle samples, and deployment of co-located sensors. Field verification data have been used to confirm the correct assignment of configuration metadata (calibration coefficients) and update software algorithms used to process raw data into derived data products.

Recommendations for further enhancement of field verification include, (1) increasing use of OOI sensors in place of ship sensors; (2) increasing verification of buoy meteorological sensors either by remaining onsite longer and/or developing mechanisms to compare ship and mooring data in real time; (3) adopting a common format for CTD sampling logs; (4) modeling platform-specific flow distortion of OOI buoys; (5) evaluating advantages of having additional data processing skills onboard; and (6) increasing ease of access for users to verification data.

PLATFORM AND SENSOR PERFORMANCE ASSESSMENT

Quantitative performance assessment of infrastructure while deployed and upon retrieval is critical to improving operational performance. A collective, comprehensive performance assessment mechanism is a future goal of the OOI. These metrics will help to optimize the OOI and inform the broader observing community of performance issues and solutions. Though a comprehensive system has yet to be developed, we include metrics where possible in examples in the following sections.

Cables and Connectors

All OOI cables are serialized and tested allowing for results to be tracked to identify trends and determine appropriate replacement cycles (e.g., neoprene cables do not appear to hold up as well as polyurethane). The OOI has collaborated with vendors to improve quality control and capture data to calculate component life cycle, predict failure, improve platform reliability, and reduce refurbishment costs. For example, between 2015 and 2017 the percentage of cables that failed the manual 50 V insulation test dropped from 30 to <5%. After the initial failure, it was discovered that the majority of the failed cables used one specific connector. Working closely with the vendor, a leak path was discovered, generated by cathodic delamination between the metal connector shell and the polyurethane material that molds it to the polyurethane cable. The vendor modified the connector design and molding process and the following year all cables passed the post-recovery test. By engaging with vendors, these technological enhancements and best practices are made more broadly available to the global observing community.

In 2016 the program shifted from manual testing to an automated cable test system for all copper wire cables. Consistent procedures have resulted in improvements in testing speed, accuracy, and data storage. Whereas manual testing for 2,500 cables in 2015 required the work of 1.1 full time employees, the automated testing of 2,000 cables in 2017 only required 0.24 full time employees. Additional adjustments include the implementation of a visual inspection regimen and cable protection and handling best practices (e.g., cages, shipping containers, strain relief, service loops, and lubrication). Lastly, instrument cables are now tested as soon as possible after recovery, since faults can disappear when cables are tested dry.

Profilers

The OOI incorporates multiple types of profilers: Coastal and Global Wire-Following Profilers (WFPs), Coastal Surface-Piercing Profilers, Cabled Deep Profilers, and Cabled Shallow Profilers. Two additional profilers (Global Array Surface-Piercing Profilers, and Endurance Array Cabled Surface-Piercing Profilers) were descoped due to poor reliability. The OOI has made significant design improvements to the reliability of the remaining profilers.

Profilers intended for long, unattended deployments on the OOI have substantial design challenges compared to fixed instrument moorings, yet offer unique advantages including collection of continuous vertical measurements. In the following subsections, we describe some challenges and successes.

Wire-Following Profilers

The Coastal and Global WFPs and Cabled Deep Profilers are based on the McLane Moored Profiler, from McLane Research Labs, Inc. The cabled profilers are additionally modified to add Wi-Fi and battery recharge capabilities. In general, OOI WFPs are robust and have been successfully deployed and maintained across the program. However, some notable operational issues remain, such as slippage, fouling, docking challenges, and power limitations.

Slippage describes the situation when the drive wheel of a WFP fails to maintain traction with the wire. Slippage occurs at either end of the profiler path, but usually at the top. This is likely associated with mooring wire motion from waves and currents, which tends to be greater near the sea surface. Parking at the top of the profile can lead to additional issues for the WFPs. Extended time in the euphotic zone can exacerbate biofouling of the onboard instruments (e.g., fluorometers and PAR sensors lack biofouling mitigation strategies). To reduce the threat of biofouling and slippage, round-trip profiling allowing parking at the bottom is used when possible.

Improvements were made to the Cabled Deep Profiler Moorings to mitigate docking challenges. The Wi-Fi antenna in the dock was redesigned allowing a good wireless connection when the profiler is parked in any orientation in the dock.

Cabled Shallow Profilers

Winched Science Pods on the Cabled Shallow Profiler Moorings have been highly reliable, as have the instruments on the accompanying 200-m stationary platforms. Some profiler issues have been noted, including failure of a dynamic seal, cable wear, and an oil leak; however, since 2015 they have successfully completed more than 27,000 profiles.

Coastal Surface-Piercing Profilers

Coastal Surface-Piercing Profilers (CSPPs) provide unique data as they are the only OOI profilers to sample across the air-sea interface. However, they also have had performance challenges.

The cabled Endurance CSPP was replaced with an uncabled version due to tether-handling issues with the winch when the profiler was near the air-sea interface and insufficient power was available from the seafloor cable due to the needed cable length. The uncabled CSPP can adaptively respond to wave motions to prevent overwrapping from snap loads, using minimal power. CSPP deployments have also been suspended at the Pioneer Array due to issues such as battery problems and breakaways. Breakaways are more problematic at Pioneer as the moorings are further offshore than at Endurance where successful uncabled CSPP deployments have taken place.

Across Endurance Array deployments, uncabled CSPPs have made round-trip profiles (upcast and downcast) 70% of planned days. The main cause of profiler stoppages is power system control problems. While improvements have been made (redesigning the battery interface, switching units from Iridium to cellular when close to shore, lengthening the antenna, etc.), some electrical, firmware, and communications issues remain.

Coastal Surface-Piercing Profilers are relatively new to ocean observing and their technology is constantly evolving as more is learned about these platforms during deployment. Work will continue to refine these profilers since they are of considerable scientific value and are the OOI's least expensive platform to buy or service.

Surface Moorings

After initial test deployments, the original design for the Coastal and Global surface buoys was improved by inclusion of hydrogen gas detection (to monitor and ensure safe hydrogen levels in the buoy well), as well as enhancements to charging circuitry, and tower design (**Figures 2A,B**). Additionally, these moorings were modified to better adapt to harsh conditions, including winds, waves, and icing. For example, during winter at the Irminger Sea Array, sub-zero air combined with waves and wind-driven spray have led to icing of the surface meteorology and air-sea flux sensors, interrupting their data collection. Technical upgrades, including heating of the buoy superstructure to prevent ice build-up, are being investigated. Work to upgrade the meteorological sensors to better cope with icing conditions and improve meteorological sensor placement to avoid flow distortion is being continually evaluated. Additional challenges include generating sufficient power during times of little wind combined with extended darkness.

BIOFOULING MITIGATION

Biofouling is an issue for a number of instruments, particularly those making optical measurements. Wipers and shutters have proven effective in keeping optical surfaces clean. The OOI implements additional biofouling mitigation measures to those provided by instrument vendors, including copper tape and silicon bronze hardware at the shallow Endurance Array sites. The use of UV-light has also been tested and is being implemented on Endurance Array cameras and Coastal and Global dissolved oxygen sensors (**Figures 2E–H**).

TECHNOLOGY REFRESH: PROCESS AND PRIORITIES

Technology refresh refers to all deployed infrastructure (e.g., sensors, platform elements, cables, and connectors). The need for a refresh process is motivated by the need for improved instrument and platform reliability and data quality, deprecation of an instrument by its vendor, and/or the existence of new instruments.

The OOI is creating a long-term programmatic strategy for technology updates. To guide this process, prioritization matrices are being developed based on lessons learned during operations for sensors, platforms, and software tools. Input from within the program, its advisory structure, and subject matter experts (SMEs) are being solicited for matrix development. These matrices will serve as programmatic best practices documentation and guidance for program planning.

SUSPENSION OF SOUTHERN HEMISPHERE ARRAYS

Budget pressures on the OOI are reflected in the decision by the NSF to scale back the Global Arrays as suggested in the "Sea Change" Decadal Survey Summary Report (National Research Council, 2015). The Argentine Basin Array has been fully terminated. Infrastructure at the Southern Ocean Array has been reduced to only the surface mooring, which is being continued with collaboration from the Natural Environment Research Council in the United Kingdom for an additional year.

COMMUNITY ENGAGEMENT

The OOI is operated as a community facility with open access to scientists, educators, and the general public. Scientists and educators can submit proposals to utilize and modify the system (adding sensors, adjusting sampling rates) and anyone can download the data from the website for free.

Since the NSF announced in 2016 it was accepting proposals to add onto OOI infrastructure, there have been 8 awards (∼20 instruments) made from NSF, United State National Aeronautics and Space Administration, United States Office of Navy Research, and the German Federal Ministry of Education and Research to add infrastructure onto the Cabled Array. The awards span two to 5 years and extend from Axial Seamount to Southern Hydrate Ridge. The instruments span geophysical – geodetic-focused sensors to examine deformation at Axial Seamount with follow-on applications at the Cascadia subduction zone, multibeam sonars to quantify the spatial and temporal evolution of methane plumes at Southern Hydrate Ridge, a multibeam sonar to image diffuse, high temperature venting at Axial Seamount, and a suite of laser raman spectrometers for an exobiology study at the

ASHES vent field. A Natural Environment Research Council-funded proposal has added nutrient sensors to the Southern Ocean Surface Mooring, and an NSF-funded proposal has adapted oxygen sampling in the Irminger Sea Array.

Not only is the OOI a resource for use by the oceanographic community, it relies on input from the broad knowledge base of the community. Community engagement allows the OOI to maximize its scientific and educational value through ancillary activities on OOI maintenance cruises (e.g., Bigham, 2018; Reimers and Wolf, 2018) and engagement with students[6] and SMEs[7] to assist with quality control efforts. The wide diversity of data types and specialized sensors requires additional effort, including SME validation of data and consistent treatment of metadata.

DISCUSSION

As described in Lindstrom (2018), the OOI helps fill a niche within the global community in the development, testing, and operation of sensors and platforms for using within an observing system. Given the diversity and volume of instruments and cables deployed long-term, the OOI has acted in many ways as a de facto laboratory and field-testing group for vendors and the oceanographic community. The development of OOI internal instrument testing pipelines and best practices as discussed in this paper can serve as a model for observatories across the globe.

Lessons have been learned in many areas since construction of the OOI began in 2009 and particularly since operations began in 2014, this paper focuses on lessons in technological development and quality control. These and future lessons in instrument and platform development, testing, deployment, and maintenance can provide a wealth of information to the global observing community as they seek to develop sustained observation systems at a variety of scales.

[6] https://oceanobservatories.org/data-workshops/

[7] https://oceanobservatories.org/researchers/subject-matter-experts/

AUTHOR CONTRIBUTIONS

KY, MK, JB, JF, MH, OK, DK, MP, AP, MV, and SW attended the OOI Lessons Learned workshop in May 2018 and contributed to the creation of an internal lessons learned report. MK led the writing of the internal report. LS wrote this paper based on that report with substantial contributions from KY and LV. AP, JF, RW, SW, JB, GC, MH, OK, MV, PM, and KN edited the manuscript, providing corrections, clarifications, and additions to the text, and images.

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REVIEW
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Tropical Pacific Observing System

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This paper reviews the design of the Tropical Pacific Observing System (TPOS) and its governance and takes a forward look at prospective change. The initial findings of the TPOS 2020 Project embrace new strategic approaches and technologies in a user-driven design and the variable focus of the Framework for Ocean Observing. User requirements arise from climate prediction and research, climate change and the climate record, and coupled modeling and data assimilation more generally. Requirements include focus on the upper ocean and air-sea interactions, sampling of diurnal variations, finer spatial scales and emerging demands related to biogeochemistry and ecosystems. One aim is to sample a diversity of climatic regimes in addition to the equatorial zone. The status and outlook for meeting the requirements of the design are discussed. This is accomplished through integrated and complementary capabilities of networks, including satellites, moorings, profiling floats and autonomous vehicles. Emerging technologies and methods are also discussed. The outlook highlights a few new foci of the design: biogeochemistry and ecosystems, low-latitude western boundary currents and the eastern Pacific. Low latitude western boundary currents are conduits of tropical-subtropical interactions, supplying waters of mid to high latitude origin to the western equatorial Pacific and into the Indonesian Throughflow. They are an essential part of the recharge/discharge of equatorial warm water volume at interannual timescales and play crucial roles in climate variability on regional and global scales. The tropical eastern Pacific, where extreme El Niño events develop, requires tailored approaches owing to the complex of processes at work there involving coastal upwelling, and equatorial cold tongue dynamics, the oxygen minimum zone and the seasonal double Intertropical Convergence Zone. A pilot program building on existing networks is envisaged, complemented by a process study of the East Pacific ITCZ/warm pool/cold tongue/stratus coupled system. The sustainability of TPOS depends on effective and strong collaborative partnerships and governance arrangements. Revisiting regional mechanisms and engaging new partners in the context of a planned and systematic design will ensure a multi-purpose, multi-faceted integrated approach that is sustainable and responsive to changing needs.

Keywords: ocean observing, tropical Pacific, TPOS 2020, user requirements, variable requirements, design, tropical moorings

INTRODUCTION

Sustained and systematic observation of the tropical Pacific Ocean has been a priority for nations around the basin since the 1980s, driven principally by the global climate effects of the El Niño/Southern Oscillation (ENSO), and by the demonstrated prediction skill based on ocean and air-sea interface observations. Increasingly planned and based on defined science goals, this Tropical Pacific Observing System (TPOS) has served the community well as a long-term and routine contribution to the Global Climate Observing System [GCOS] (2014a,b), delivering measurements that advance our capability to describe, understand and predict ENSO and climate variability more generally (McPhaden et al., 1998, 2010).

The TPOS supports research that underpins improvements in prediction and contributes to detecting climate change. Benefits of the TPOS manifest over multiple sectors and into regions remote from the tropical Pacific; agriculture and water management (Sassone and Weiher, 1997; Lazo et al., 2011; World Meteorological Organization [WMO], 2012; Centre for International Economics, 2014), marine ecosystems and fisheries (Chavez et al., 2014; Tommasi et al., 2016), human health and well-being (Fischer et al., 2010; World Meteorological Organization [WMO], 2012), disaster preparedness (Hoeke et al., 2013; Cashin et al., 2014; Harrison et al., 2014) and health/well-being of terrestrial living systems (Intergovernmental Panel on Climate Change, 2014) are just some of the sectors that benefit directly and indirectly from the TPOS, often via sophisticated El Niño prediction systems.

The TPOS came under pressure during the period 2012–2014 when logistical and other support for the Pacific tropical moored buoy array (TMA) was reduced, leading to inferior data returns (around 40% compared with the usual 80–90%; see Figure 1-1 in Cravatte et al., 2016) and, in the western Pacific, a phased decommissioning of around thirteen sites. The central and eastern Pacific data returns were back to normal by 2015, but there are now only two TRITON sites west of 165E. Several studies suggest this degradation compromised our ability to monitor climate variability and consequently to model and predict ENSO (Tollefson, 2014; Fujii et al., 2015, 2019; Chiodi and Harrison, 2017a,b; Xue et al., 2017). This challenging period should be seen in the context of a TPOS capability that had grown significantly over the last two decades and highlighted points of vulnerability that were not well understood or managed (Ando et al., 2017; Serra, 2018). The TPOS 2020 Project was initiated to improve our understanding of the collective TPOS capability, beyond its individual parts, and to provide a stronger, more capable integrated approach with improved governance and management of risk (see the TPOS 2020 First Report, Cravatte et al., 2016, hereafter referred to as the First Report). In doing so, improved knowledge of relevant phenomena and spatiotemporal variability are considered for the design, and emerging technologies and new techniques will form part of the recommended response to requirements.

The TPOS 2020 Project does not directly consider regional and local requirements and observing system responses. Global Climate Observing System [GCOS] (2014b) included two papers that addressed Pacific Island (Wiles et al., 2014) and eastern Pacific (Takahashi et al., 2014) regional needs and these were considered by Cravatte et al. (2016). The priority given to the western Pacific (see The TPOS 2020 First Report and Low-Latitude Western Boundary Current Systems) partly reflects the demand for improved severe weather and climate outlooks. Section "Eastern Pacific" discusses some of the eastern Pacific coastal aspects.

BACKGROUND ON TPOS DESIGN AND PROCESS

The TPOS 2020 approach to the initial design (**Figure 1**) followed the Framework for Ocean Observing (Lindstrom et al., 2012; Tanhua et al., 2019, this issue), beginning with an analysis of user demand, then the driving phenomena, and followed by specification of the required sampling (essential variables, spatiotemporal characteristics, quality, etc.). With this approach, Essential Ocean Variable (EOV) requirements do not tell us which platforms or techniques are needed but establish a target for the collective observational capability (the general and specific responses). A variable requirement may be responding to multiple needs and uses, including those underpinning basic scientific research.

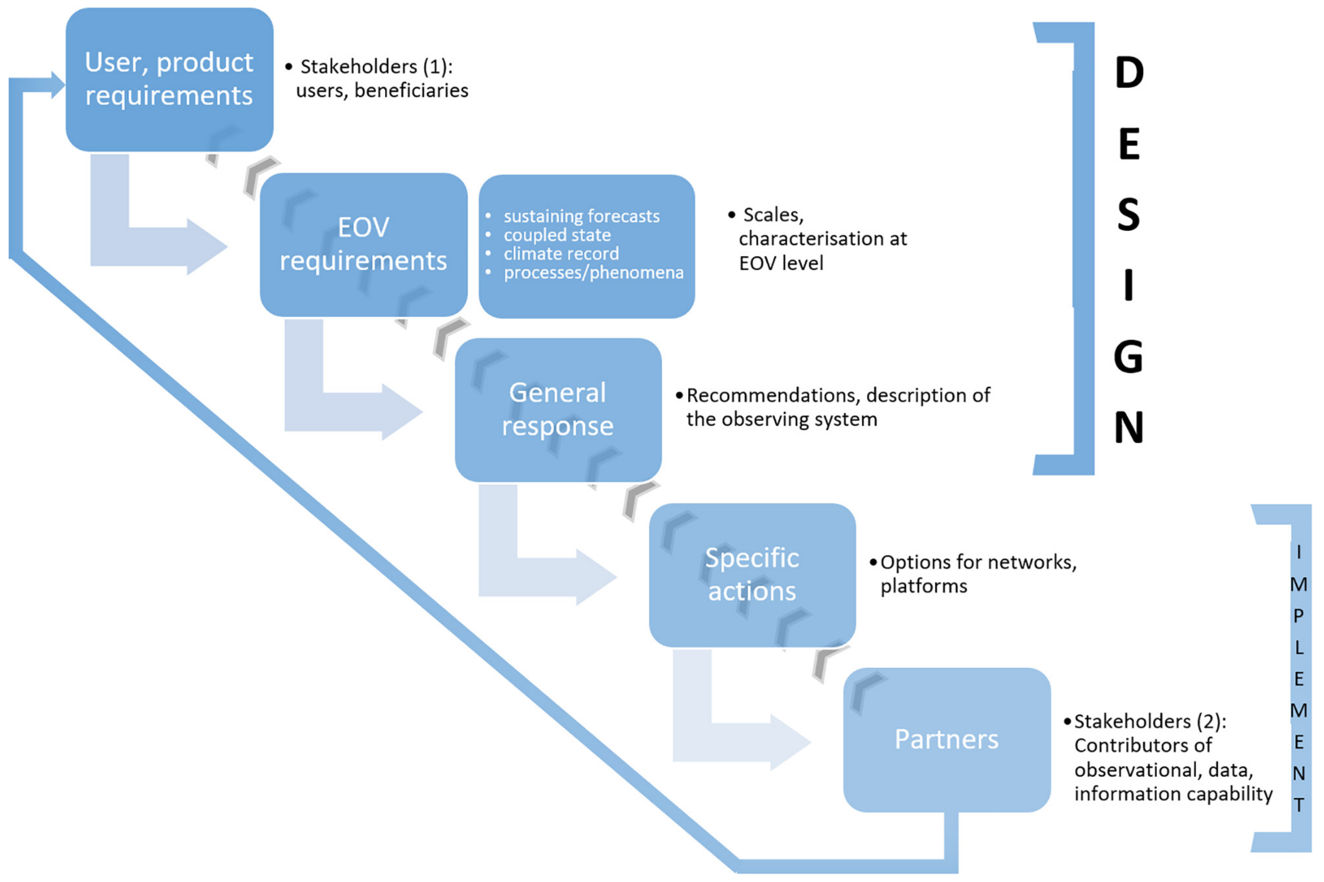

FIGURE 1 | Schematic of the process deployed by TPOS 2020 in the First Report (an adaptation of the Framework for Ocean Observing, Lindstrom et al., 2012). The design is user driven and some form of stakeholder "market" analysis is required to define needed products, including resolution, accuracy and so on. In some cases (e.g., research) the users may provide this specification in terms of variables. The second level is a set of requirements expressed in terms of characteristics (scales, etc.) of Essential Ocean/Climate Variables. At the next level the TPOS 2020 considered a general response in the form of recommendations; these may be thought of as observing system requirements. The specific response (level four) is expressed as a set of actions and recommendations at the level of networks and platforms. Finally, and most importantly, partners in the TPOS (a 2nd set of stakeholders) contribute the needed observational capability and capacity. Feedback occurs as part of the process, and directly between the final level (partners) and users/beneficiaries (the arrows from bottom right to top left).

The design stage, and establishing requirements in particular, is critical for priority setting. The user and product requirements determine essential inputs which are expressed in terms of EOVs. Priorities are established for the general response and specific actions based on these higher-level requirements. It is a subjective process, relying on experts and stakeholder feedback.

End-user engagement is built into the TPOS 2020 approach, through its governance and through its review process, whereby both experts and general stakeholders (users of data; providers of data; beneficiaries) are invited to critique the design.

The recommended general response and specific actions of the TPOS 2020 initial design comprises a mix of experimental and sustained approaches, and it is the latter that constitutes the Backbone of TPOS: the fundamental and core contributions to the sustained observing system (Cravatte et al., 2016). The recommendations of the First Report for the Backbone are generally not platform-specific, nor do they refer to any single nation or individual effort. They are written in a form that prioritizes need but otherwise leaves flexibility in the hands of the providers and operators of measurement networks (see Section "Phased Changes to the Backbone" for further detail).

The recommended response is generally an ambitious target and, if fully met, represents the ideal observing system strategy for the tropical Pacific.

THE TPOS 2020 FIRST REPORT

The First Report (Cravatte et al., 2016) takes advantage of developments in both satellite and *in situ* networks over the last 20 years, including multiple scatterometers, multiple altimeters, global Argo and advances in mooring and other technology. It advocates for an integrated, multi-faceted approach in which *in situ* systems support satellite measurements, and vice versa, and the strengths of particular platforms are brought together to produce an observing system that is stronger than the sum of its individual contributions.

The Rationale Behind the Reconfiguration of the Backbone

The new Backbone TPOS design aims to deliver to five key functions:

(1) Provide data in support of, and to evaluate, validate and initialize, ENSO prediction and other forecasting systems and to foster their advancement;
(2) Provide observations to quantify the evolving state of the surface and subsurface ocean;
(3) Support integration of satellite and *in situ* approaches including calibration and validation;
(4) Advance understanding and modeling of the climate system in the tropical Pacific, including through the provision of observing system infrastructure for process studies; and
(5) Maintain and extend the tropical Pacific climate record.

Present and future elements have been assessed against their ability to deliver to these functions, with high priority given to those that contribute to many uses. This framework, along with the development of the capabilities of Argo and space-based sensors, leads to a reassessment of the role of the TMA. Moorings' unique capabilities provide excellent temporal resolution of many different oceanographic, meteorological, and biogeochemical EOVs, enabling diagnosis of the spectral characteristics of phenomena and specification of the errors inherent in sparser-in-time sampling. They can provide collocated ocean and atmosphere observations, with the full suite of variables to estimate air-sea fluxes. However, today Argo greatly improves the vertical resolution of subsurface features, and samples between the TMA lines, while satellites provide unprecedented spatial coverage and resolution, capturing the synoptic atmospheric variability that partly drives the net surface fluxes.

In the new TPOS Backbone, we have sought to exploit the complementarities among platforms to underpin a major advance in our capability to monitor the tropical Pacific Ocean and surface atmosphere. We approach the observing system as a network, where individual components, each with their strengths, combine to provide robustness, reinforcement, cross-checking, and greater overall resilience. We see state estimation and its exploitation of this complementary between satellite and *in situ* observations as fundamental, empowering both research and operational users of the observing system. Beyond the goal of tracking the system state, TPOS 2020 has also targeted observations needed to challenge and help improve model physics (Cravatte et al., 2016; their section 2.6.8), particularly for mixing and ageostrophic dynamics on the equator and upper ocean-atmosphere coupling at sub-daily timescales. Associated with this latter challenge is the need to describe these processes across key weather and ocean regimes.

Maintaining a credible climate record across a redesign of the observing system has been a challenging and at times controversial aspect of this project. It was risk to the climate record which drove the creation of the TPOS 2020 project, with deterioration of the TMA in the early 2010s giving a concrete demonstration of the precariousness of long-term observations. Changing locations and sampling patterns of longstanding measurements may cause a loss of some information but insisting that time series of every variable or site be maintained in the context of changing observing technology, science issues and user needs is not compelling. A climate record is more than a time series at a point (Cravatte et al., 2016); in reality it comprises any systematic observations that accurately describe the evolution of phenomena.

For TPOS 2020, balancing the requirements of maintaining a credible and robust climate record against new requirements and opportunities occupied many months of study and debate, and indeed, has directed much of our work. We are striving for a balance between detecting long term change across the full TPOS and making new observations that will fuel novel insights into key processes and challenge the next generation of coupled models.

Recommendations for an Integrated Backbone

In the new TPOS Backbone the function of monitoring the state of the ocean and air-sea interface will be largely delivered through a combination of satellite-based sensors, autonomous floats and a reconfigured moored array, along with traditional elements of the observing system (e.g., drifters, high-resolution XBT, tide gauges, hydrographic sections), while the function of driving forward our understanding of key regimes and poorly understood physical processes will be delivered through enhancements that might inform on potentially missing elements. The special role that some *in situ* measurements play for the calibration and validation of space-based observations, including multiple mission products, will also be preserved or enhanced.

The major recommendations from the First Report are given below, with focus on those that represent a specific TPOS response (refer to the Executive Summary http://tpos2020.org/first-report/ for details; recommendations are referenced in [brackets]).

Air-Sea Interface Surface Variables

- Improve coverage and reduce diurnal cycle aliasing of vector winds with a constellation of multi-frequency scatterometer missions and complementary wind speed measurements from microwave sensors and *in situ* to enable all-weather wind retrievals over 90% of the tropical Pacific Ocean every 6 h [Recommendations 1, 2]. *In situ* wind and surface current data play a vital role as reference data and in the climate record.
- Continue and enhance space-based precipitation measurements complemented by expansion of the *in situ* moored siphon rain gauges covering diverse rainfall climate regimes [Recommendations 8, 9].
- Enhance *in situ* observations of the state variables needed to estimate the full surface heat and freshwater fluxes, with emphasis given to key regimes and promoting pilot studies of new platforms. This will be accompanied by the promotion and support of studies to improve wind stress products and to understand the sensitivity and impact of

observed air-sea flux variables in forecast and reanalysis systems [Recommendation 15 and Actions 6–11].

- Continuation of high-frequency, moored time series and broad spatial scale underway surface ocean pCO_2 observations across the Pacific from 10°S to 10°N [Recommendation 12].
- Continuity of complementary satellite and *in situ* sea surface salinity (SSS) measurement networks, with a focus on improved satellite accuracy [Recommendation 10]. Recent results (e.g., Boutin et al., 2018; Hasson et al., 2018) show improvements in the quality of SSS retrievals, encouraging TPOS 2020 to review this recommendation.
- Recommendations for other surface variables (sea surface temperature (SST), sea surface height, ocean color, mean sea level pressure) follow those of other global observing system plans (for example, Global Climate Observing System [GCOS], 2016) [Recommendation 3–7, 13]; the importance of passive microwave SST measurements is highlighted.
- Existing technologies cannot meet surface current velocity requirements. The First Report encourages efforts to measure surface velocity from space [Recommendation 11].

Subsurface Variables

- Broad-scale sampling of subsurface temperature and salinity is required, with enhanced resolution through the tropics, and better meridional spacing and increased vertical resolution in the equatorial region. Additional targets are to resolve near-surface salinity stratification and to improve sampling of equatorial currents [Recommendations 16–20]. More specifically:
  - Target the fast, coupled upper ocean physics across key regimes: enhance mooring resolution in the upper layer and expand the moored array poleward to give broader coverage and better temporal resolution of faster processes and the parameters needed to estimate total surface fluxes and the mixed layer response;
  - Double Argo profile returns between 10°N – 10°S, starting in the western Pacific;
  - Restore the equatorial moored array in the west;
  - Target the circulation and physics on the equator: maintain and expand direct measurements of velocity on the equator across the basin; and
  - Expand direct velocity sampling, initially at 140°W, to better resolve the meridional structure of the Equatorial Undercurrent (EUC) and the advection and mixing processes where the EUC interacts with the mixed layer.

The value added from the proposed TPOS 2020 Backbone is sketched in **Figure 2** while **Figure 3** shows the proposed changes to the core TMA mooring configuration. Mooring sampling is returned and enhanced to the equatorial west Pacific west of 165°E and the TMA is reconfigured and enhanced elsewhere (**Figure 2**, top panels). Surface mooring enhancements provide the full flux variables needed for bulk flux estimation. Velocity measurements are increased from TMA near the surface and subsurface (**Figure 2**, 2nd and 3rd panels down; **Figure 3**) while doubling Argo enhances the sampling of temperature and salinity in the equatorial region (bottom two panels). The reconfiguration of the moored array and Argo from its present form should be staged in a way that allows testing and evaluation and an orderly transition. Discussions have commenced on the technical detail and on how the transition should be managed (see Phased Changes to the Backbone).

FUTURE FOCI OF THE TPOS 2020 PROJECT

Biogeochemistry and Ecosystem Contributions

Autonomous observing and forecast development has expanded beyond physical parameters. Past TMA physical data have been of great value for the development of next generation ecosystem and operational fisheries forecasts, but biogeochemical observations are necessary to make further improvements in these models. The region's large carbon signal and economic reliance on diverse and productive ecosystems emphasize the need to advance understanding of tropical Pacific biogeochemical variability and predictability.

The tropical Pacific is a region with unique and highly variable biogeochemical signatures over space and time (**Figure 4**). This region is the largest oceanic source of CO_2 to the atmosphere, supplying up to 1 petagram of carbon annually with considerable ENSO-driven interannual variability (e.g., Chavez et al., 1999; Feely et al., 2006). Poor constraint of these large interannual signals could double the uncertainty in annual carbon budgeting of CO_2 emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere (Le Quéré et al., 2018). Globally, ocean warming and stratification are causing a decline in oceanic dissolved oxygen. Models suggest that further expansion of the already extensive Oxygen Minimum Zone (OMZ) in the tropics could reduce habitat, shift distributions of marine species, and change ecosystem structure (Stramma et al., 2012).

Despite being iron-limited, tropical Pacific waters are moderately productive above the OMZ and serve as globally significant regions of biologically fueled carbon sequestration (Mathis et al., 2014). The organic matter produced in the eastern and central tropical Pacific that escapes upper ocean remineralization is exported to the deep ocean. Conversely, in the warm pool thermal stratification restricts subsurface nutrients from entering the euphotic zone, resulting in low surface nutrients, primary productivity and carbon export.

The western boundary currents feeding the EUC partially regulate biological productivity through entrainment of iron from the shelves (Ryan et al., 2006). Further upstream, these feeder currents also derive pre-formed inorganic carbon from the surface of the north and south Pacific and dissolved inorganic carbon, due to remineralization, as they transit toward the EUC. Both of these processes contribute to the upwelling and degassing of CO_2 in the central and eastern Pacific. Quantifying the volume fluxes into the EUC is important for understanding the relative importance of local versus remote forcing to the observed

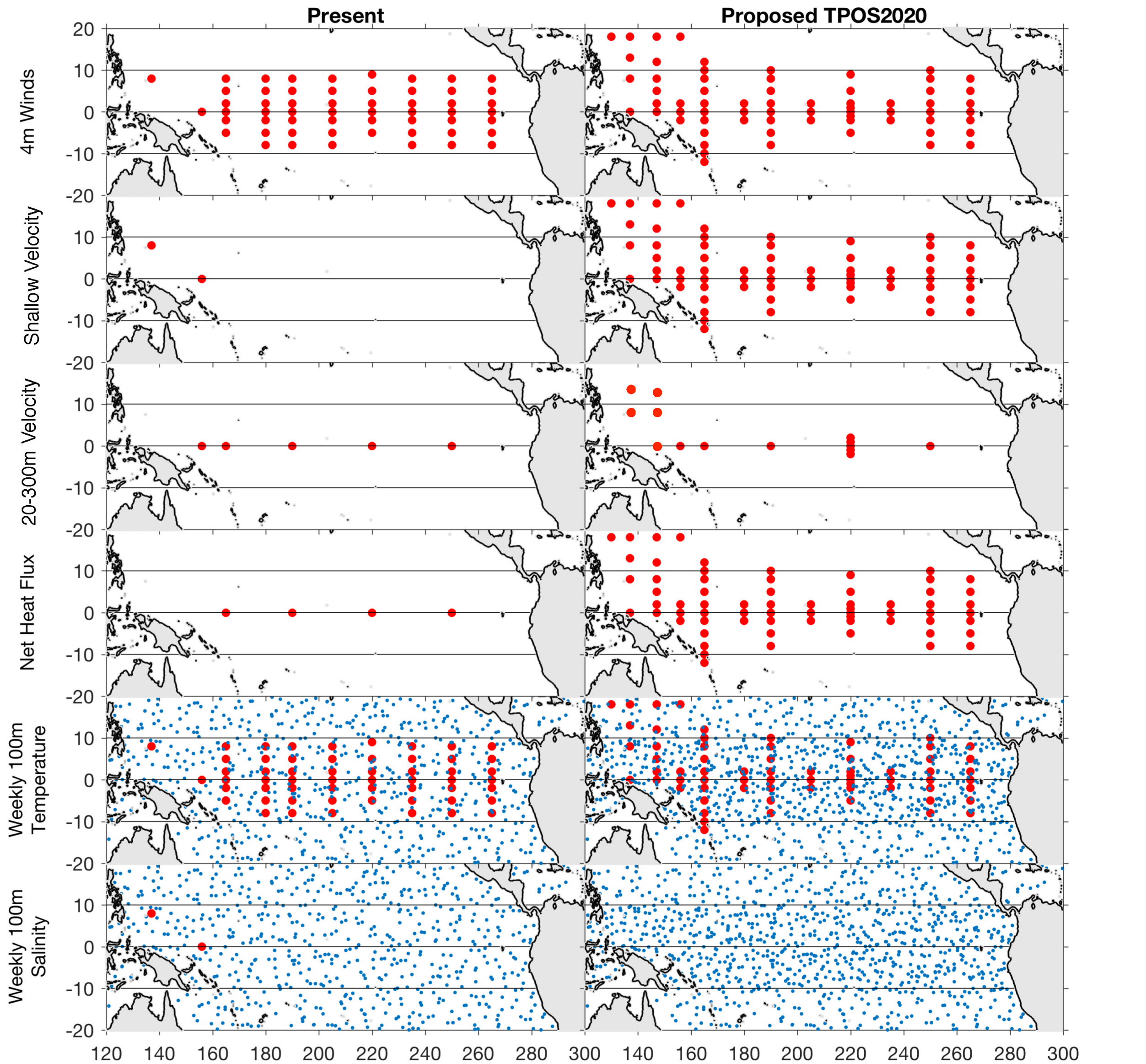

FIGURE 2 | Schematic showing data returns from the TMA and Argo for key variables of interest between the present observing system **(left)** and the proposed TPOS 2020 Backbone **(right)**. Observations from the TMA are shown in large circles and Argo in smaller dots. Improvements in surface flux, velocity and subsurface sampling are expected. Further extensions of the TMA are under consideration.

variability in biological productivity and air-sea CO_2 fluxes. In addition to these applications to biogeochemistry, inflow to the EUC is also central to understanding the heat and freshwater budget of the tropical Pacific, which was discussed at length in the First Report.

Primary productivity in the southeastern tropical Pacific supports the largest single species fishery in the world, the Peruvian anchoveta, where real-time TMA data are used to make present-day fisheries management decisions. The western and central tropical Pacific supports over 50% of the global tuna industry, a significant resource (as much as 40% of the Gross Domestic Product) for the region's island nations (Lehodey et al., 1997; Chavez et al., 2003). Abundance and distribution of these fish populations correlate with ENSO (and in some cases Pacific Decadal Oscillation); however, it is not clear how the coupling between physics and biogeochemistry drive changes at these higher trophic levels (Chavez et al., 2014). Tropical Pacific physical fluctuations have a deep impact on these and other living marine resources, including protected species such as coral reefs, sea turtles, and cetaceans.

Initial recommendations for integrating biogeochemistry into TPOS focused on (1) sustaining and expanding established observations, such as air-sea CO_2 fluxes and satellite ocean color and (2) pursuing data synthesis and new technology pilot projects to refine the critical time and space scales for biogeochemistry (Cravatte et al., 2016). The final backbone observing system

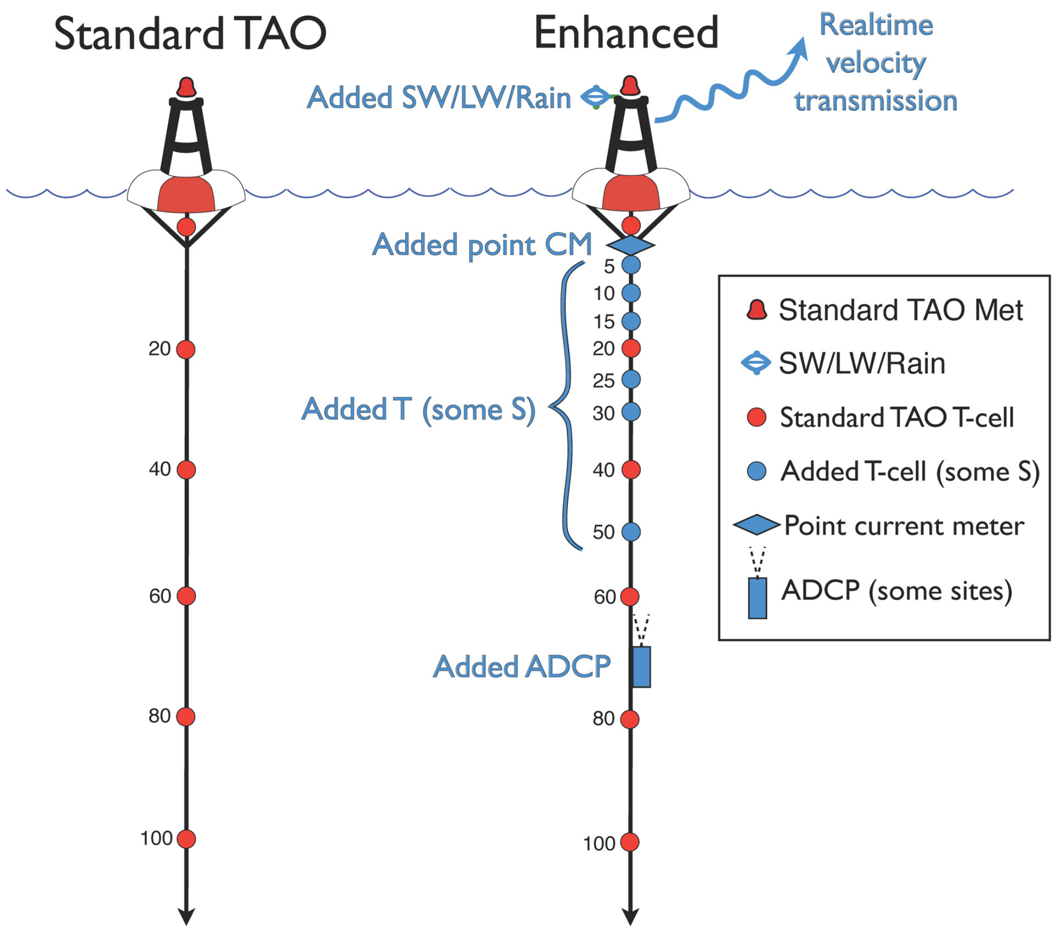

FIGURE 3 | Schematic of recommended enhancements to standard TAO moorings. Standard measurement suite shown in red; enhancements in blue. Depths (m) of the subsurface instruments are listed by each symbol. The enhancements are designed to provide quantities for bulk flux estimation and to take advantage of moorings' high temporal sampling rates for the rapid-evolving, short-vertical-scale phenomena of the surface mixed layer, including velocity. Shallow velocity measurements are also needed to reference satellite scatterometer winds to the surface current, a particular problem in the tropics where currents are strong and winds relatively weak.

design must provide additional key observations that will underpin research to better understand both climate impacts and connections to higher trophic levels. The biogeochemical and ecosystem processes of the tropical Pacific driving this design are:

- tropical Pacific biogeochemical and ecosystem response to climate change, including consequences of OMZ variability and change to higher trophic level habitat;
- seasonal to decadal variability of the Tropical Pacific biological pump to allow biogeochemical model/forecast development and assessment of ecosystem impact;
- seasonal to decadal variability of tropical Pacific CO_2 flux and implications for the global carbon cycle;
- upper ocean carbon budget including carbon export below the mixed layer and sources of anthropogenic carbon to equatorial Pacific upwelled water; and
- volume and nutrient fluxes into the EUC to understand how this variability modulates biological variability in the central and eastern Pacific.

These processes drive the major biogeochemical requirements in TPOS to maintain a climate record of air-sea CO_2 flux and to resolve seasonal to interannual water column variability of inorganic carbon, oxygen, chlorophyll, particles, and nutrients, which are all EOVs. These requirements can be met by maintaining air-sea CO_2 records on ships of opportunity and buoys (including new sites in the western Pacific), enhancing at least one third of Argo enhancements in the region with biogeochemical sensors, re-establishing CTD and bottle sampling on mooring servicing cruises to 1000 m, and continued biogeochemical-related satellite programs.

Biogeochemical (BGC)-Argo observations in the tropical Pacific have the potential to characterize seasonal to interannual variability of dissolved oxygen and the OMZ, inorganic carbon, chlorophyll, and nitrate, as well as the mechanisms driving the biological pump. BGC-Argo data combined with ship-based validation data and surface ocean CO_2 flux measurements could also be used to estimate vertical gradients in carbon chemistry, to calculate upper ocean carbon

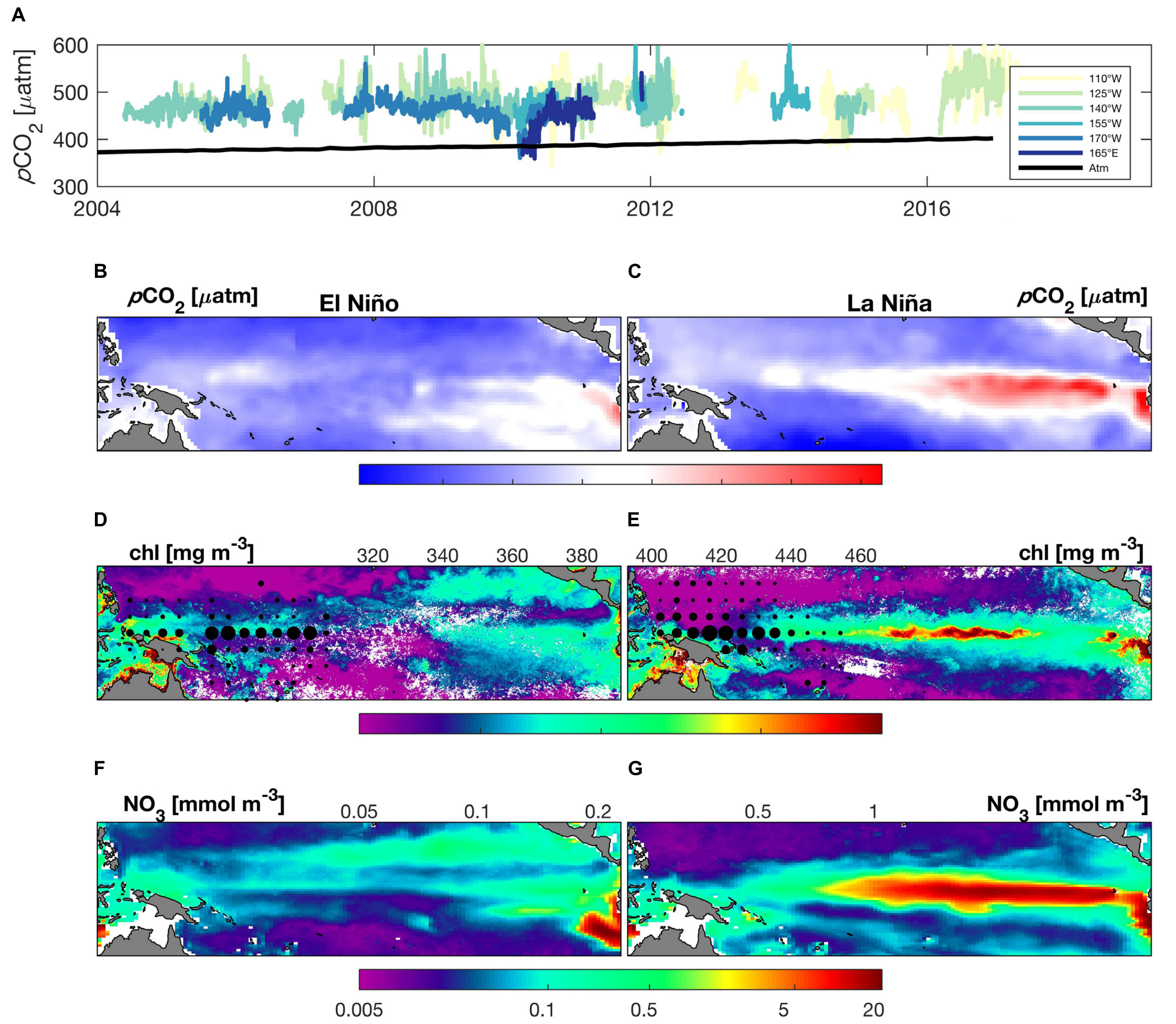

FIGURE 4 | Summary of long term trends and example El Niño (January 1998) vs La Niña (July 1998) conditions for important biogeochemical parameters. **(A)** Long term trends in surface ocean and atmospheric pCO_2. The colored lines indicate surface ocean pCO_2 from tropical Pacific moorings, all at 0° (Sutton et al., 2018). The black line is atmospheric pCO_2 (in ppm) from a station on Easter Island (Dlugokencky et al., 2018). **(B,C)** Gridded surface ocean pCO_2 from Landschützer et al. (2017). **(D,E)** SeaWiFS satellite monthly mean surface chlorophyll concentration. The filled circles represent the magnitude of the skipjack tuna catch for El Niño (**D**, January–June 1992) and La Niña (**E**, January–June 1989), adapted from Lehodey et al. (1997). **(F,G)** Surface nitrate concentrations from the NASA Ocean Biogeochemical Model (NOBM; Gregg and Casey, 2007; https://giovanni.gsfc.nasa.gov/giovanni/). The latitude/longitude domain in **(B)** through **(G)** is 20°N to 20°S, 120°E to 80°W.

budgets and export. Maintaining and expanding high-quality observations (surface pCO_2 and ship-based bottle samples) will be required to validate new and emerging platforms and biogeochemical sensors like BGC-Argo and autonomous surface vehicles.

Sustained, repeat hydrographic surveys of biogeochemical observations would provide the opportunity to measure biogeochemical phenomena that cannot currently be measured autonomously and provide a climate-quality time series to validate autonomous sensors with larger measurement uncertainties. On mooring servicing vessels, the CTD package should be equipped with dissolved oxygen and optical sensors. Water samples for chlorophyll and nutrients should be routine, while other GO-SHIP parameters such as dissolved trace elements, inorganic carbon, particulate organic carbon, transient tracers, N_2O, C isotopes and dissolved organic carbon should be accommodated where possible, probably through the involvement of funded investigators. These measurements should continue on GO-SHIP voyages (on average, one GO-SHIP voyage per year intersects the tropical Pacific), as well as process study cruises.

These backbone observations combined with process studies and continued observing technology development would be foundational to biogeochemical model development and assessments of current and future ecosystem impact. Occasional quantification of volume fluxes into the EUC in conjunction with biological pump process studies and modeling efforts, for example, would help to identify how iron sources drive biological production and carbon export. This would address how coupling between physics and biogeochemistry drives changes at higher trophic levels and how sensitive biological carbon drawdown is to variability and change. This would also constrain anthropogenic signals in the dissolved inorganic carbon content of the EUC and its source waters.

If implementation of biogeochemical observations needs to be geographically targeted, the areas of greatest interest for subsurface oxygen measurements are the eastern and central tropical Pacific, because of the key role that OMZs play there. For water mass properties and provenance, the low-latitude boundary currents and the western EUC are most important because of the role they play in delivering natural and anthropogenic inorganic carbon to the central and eastern Pacific. For air-sea CO_2 fluxes and nutrient variability, it is important to map the entire tropical Pacific likely with a combination of ship transects, BGC-Argo and autonomous surface vehicles.

In summary, the observing system should:

- provide air-sea CO_2 observations on buoys, including new sites in the western Pacific
- map basin-wide surface CO_2 variability with ships or autonomous surface vehicles
- instrument at least one third of Argo float enhancements in the region with biogeochemical sensors
- re-establish CTD and bottle sampling for biogeochemical parameters on mooring servicing cruises
- incorporate biogeochemical observations on repeat hydrography voyages
- continue advocacy for biogeochemical satellite programs
- provide a backbone for biogeochemical process studies and ecosystem observations

The long-term vision is that through coupled physical and biogeochemical observations, process studies, and model development, TPOS can better serve the research community and ultimately inform marine resource management and protection.

Low-Latitude Western Boundary Current Systems

The western equatorial Pacific is a principal conduit from the subtropics to the equator for thermocline and intermediate waters (Fine et al., 1994, see **Figure 5**). Low-Latitude Western Boundary Currents (LLWBCs) – the Mindanao Current (MC) in the northern hemisphere and the complex current system in the Solomon Sea in the southern hemisphere – transport waters of subtropical or higher-latitude origin toward the equator (Hu et al., 2015). These waters either exit the basin through the Indonesian seas via the Indonesian Throughflow (ITF), or feed the equatorial current system (Tsuchiya et al., 1989; Lukas et al., 1996; Fukumori et al., 2004; Grenier et al., 2011). At interannual ENSO timescales, LLWBC transport variations are comparable in magnitude to the interior transport variations: they are thus an essential part of the recharge/discharge of equatorial warm water volume (Lee and Fukumori, 2003; Izumo, 2005; Ishida et al., 2008; Qin et al., 2015) so measurements of their transport and properties are important for understanding, diagnosing and predicting ENSO events. LLWBC transports can also vary at decadal timescales, possibly contributing to decadal modulation of the background state of the equatorial band (Lee and Fukumori, 2003), although this decadal variability is largely unconstrained by observations. Finally, despite very different representation of these currents across climate models, major long-term changes are consistently predicted, including an acceleration in the southern hemisphere of the New Guinea Coastal Undercurrent and deceleration of both the MC and ITF (Hu et al., 2015; Sen Gupta et al., 2016). As such, the LLWBCs and the ITF represent major contributions to the mass, heat, and freshwater budget of the tropical Pacific (Roemmich et al., 2014; Cravatte et al., 2016).

The western Pacific is a primary source of macro and micro-nutrient (particularly iron) enrichments through land-sea exchanges including river discharges, hydrothermal sources, sediment inputs from the shelves and slopes, and through aerosol (notably volcanic) deposition (Mackey et al., 2002; Ryan et al., 2006; Slemons et al., 2009, 2010; Gorgues et al., 2010; Radic et al., 2011; Grenier et al., 2013; Labatut et al., 2014; Qin et al., 2016; Ganachaud et al., 2017). LLWBCs are thus also conveyor belts for micro-nutrients from the western continental margins to the central and eastern Equatorial Pacific upwelling regions, via the EUC; these remote nutrient supplies are critical for maintaining the high levels of biological productivity in this region (Mackey et al., 2002; Slemons et al., 2010, 2012; Grenier et al., 2013; Qin et al., 2016). Better understanding of the enrichment processes and transport variability is important to infer the changes in primary productivity in the eastern equatorial basin. This productivity affects the regional food web that underpins critical tropical fisheries (Bell et al., 2011) and also plays a role in the levels of pCO_2 in surface waters and transferring carbon to the deep ocean.

Requirements for a LLWBC Observing System

LLWBCs are deep, narrow, powerful, and variable currents, flowing within a few 10 km from the coast, and are therefore challenging to observe. They require specialized instrumentation and integration across multiple platforms to adequately describe the connected fluctuations. Developing a LLWBC monitoring plan requires addressing several issues: identifying the users of a sustained monitoring system; assessing the relative importance of real-time and long-term sampling; determining the priority variables to be measured, their sampling accuracy and spatial and temporal timescales.

LLWBC and ITF heat transports are a first-order term in the evolution of equatorial warm water volume in all phases of ENSO. This suggests that simultaneous real-time monitoring of the combined LLWBC/ITF heat transport variability would enable a qualitative advance in ENSO and tropical Pacific climate

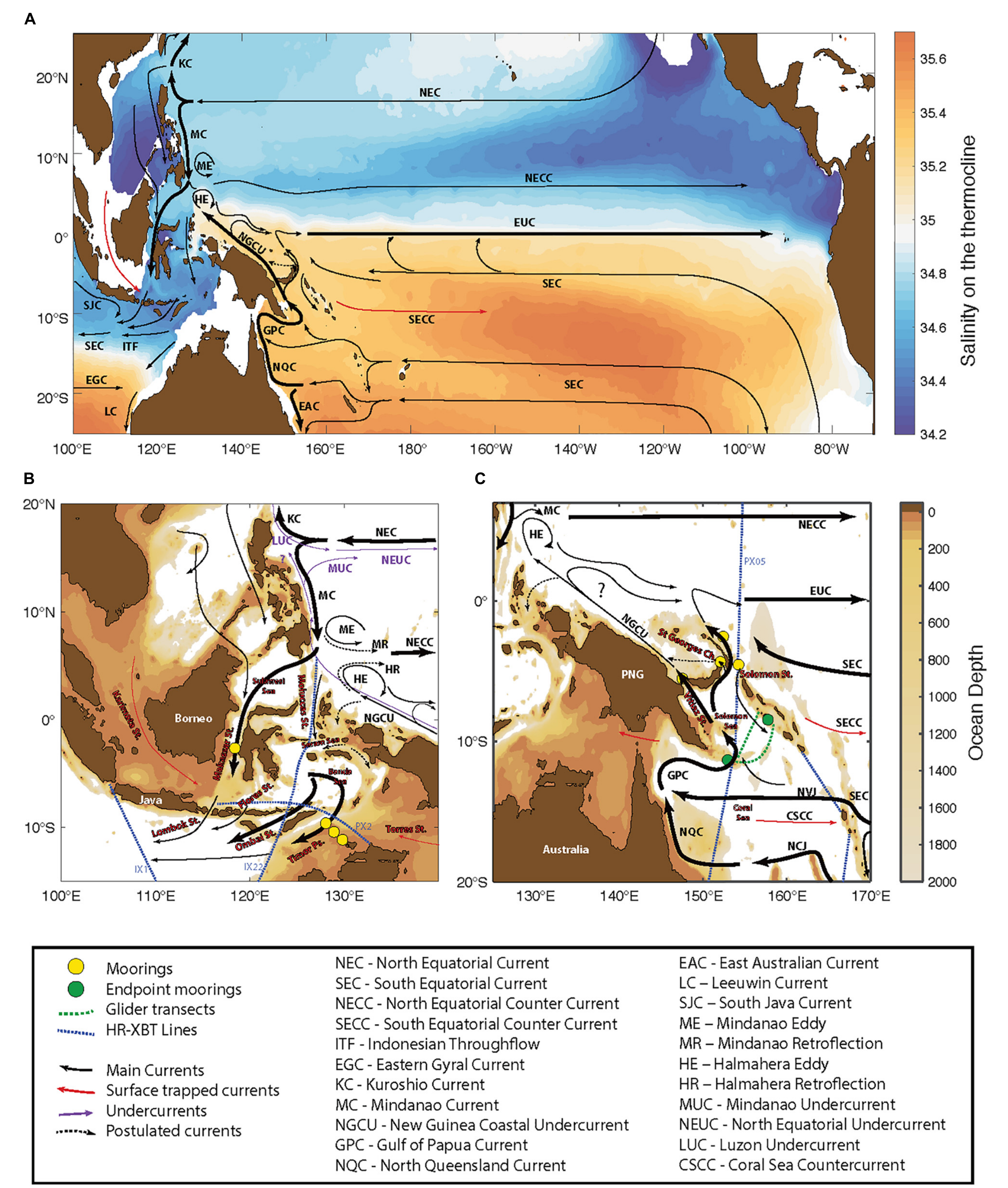

FIGURE 5 | Schematic showing the main circulation features for **(A)** the tropical Pacific, **(B)** the Indonesian Seas and **(C)** the tropical western Pacific. In **(A)** color shading shows mean salinity at thermocline level (20°C isotherm depth is used as a proxy) based on the BRAN2016 reanalysis (Oke et al., 2012); scale at right. Arrows highlight the flow pathways: Black at thermocline depth (thicker arrows are stronger), red for very shallow flows, dashed for postulated flows. Current names are listed in the legend at bottom. In **(B,C)** the brown shading shows the bathymetry (scale for both at right). Again arrows highlight the flow pathways, with purple arrows for undercurrents. Other observational arrays, including moorings, glider and XBT lines are added (legend).

diagnostics. The result, if implemented, would serve climate diagnostics and outlooks for expert assessments at climate and seasonal forecast centers. In addition, LLWBC observations could serve for constraining, validating and improving model simulations (Balmaseda et al., 2014) in this region where model resolution is often too coarse to resolve the narrow straits and complex bathymetry and be key to better understanding decadal/longer term modulation of ENSO.

For this purpose, monitoring the heat transport on monthly/seasonal timescales should be the target with vertical profiles of velocity and temperature observations. Ideally, monthly temporal resolution is needed for forecasting purposes and seasonal for change detection; given the high-frequency transport variability, this would imply a sampling at higher temporal resolution than monthly. We should strive to measure the entirety of the LLWBCs heat transport, coast to coast when it is constrained by bathymetry, or at locations appropriate to capture its horizontal extent. As much of the variability occurs in the upper 0–500 m this is the early priority, if possible extending deeper to capture the intermediate water transport; while monitoring the transport to the sill depth of the passages would be an ultimate goal from long-term climate perspectives.

In the following, we briefly discuss the main LLWBC features, learnt from the past or current process studies in the southern and northern hemispheres and in the ITF. We present a monitoring strategy with appropriate locations and platforms to respond to the above requirements.

The Southern LLWBCs: The Solomon Sea

In the southern hemisphere, the New Guinea Coastal Current (NGCC) system is composed of several branches that split within the Solomon Sea, a semi-enclosed sea acting as a bottleneck. The main branch flows as an undercurrent through the southern entrance within a narrow band closely tied to the coast, carrying mostly subtropical waters that flow up the coast of Australia in the Gulf of Papua Current (GPC; Kessler and Cravatte, 2013). The GPC/NGCC mixes with tropical waters that flow directly into the Solomon Sea. Inside the Solomon Sea, westward and eastward branches of the NGCC exit northward through Vitiaz Strait, St. George's Channel and Solomon Strait (**Figure 5**).

Transport flowing through the Solomon Sea is highly variable at intraseasonal, seasonal and interannual timescales (see Ganachaud et al., 2014, 2017; Germineaud et al., 2016, for reviews). Large interannual transport variations, strongly modulated by ENSO, occur mainly in the top 250 m.

During the past decade since OO'09, international field campaigns in the Solomon Sea as part of the CLIVAR-SPICE program, have provided a testbed for sampling strategies. The main difficulty in observing the heat transport in this region is due to bathymetry splitting the LLWBCs into numerous branches, the narrowness of some passages (rendering the use of altimetry as a first-order proxy for mass transport inadequate), and the narrow current widths close to coastlines (and so not well sampled by broadscale Argo profiles). Integration across various observational networks in this region is essential. Full-depth subsurface moorings have been deployed in the straits for periods of 1.5–3 years (Ganachaud et al., 2017); repeated glider transects across the southern entrance of the Sea have proven to be an adequate solution for providing estimates of coast-to-coast equatorward heat and freshwater transport to 1000 m, though transects can be aliased by eddies (Davis et al., 2012); Pressure Inverted Echo Sounders (PIES) and high density XBT transects have been combined with altimetry and Argo floats to infer the mass transport interannual variability through the Solomon Sea (Melet et al., 2010; Zilberman et al., 2013). They are capable of quantifying many time scales of the volume transport of the NGCC system.

At present, the mass and heat and freshwater transports across the Solomon Sea southern entrance are sustainably monitored, with PIES/altimetry providing high resolution estimates of the mass transport, and repeated glider transects (better than monthly) providing in real-time vertical structure and property measurements. These should be maintained. Glider sampling must be frequent due to vigorous mesoscale eddies that result in high-frequency transport variability. Resolving monthly variability would require several transects per month, which seems as yet unrealistic.

Beyond monitoring transport and properties entering the Solomon Sea from the South Pacific, additional value would come from monitoring the exits to the equator, for two reasons. First, important mixing and water mass modification occurs inside the Solomon Sea (Melet et al., 2011; Alberty et al., 2017). Second, the partitioning between the three exit straits leads to three distinct pathways connecting the Solomon Sea to the equator, that models indicate have highly disparate transit times and ultimate destinations (Grenier et al., 2011; Qin et al., 2015). Resolving this partitioning appears to be important for the timescale of the impacts on the equatorial region, resulting in feedback processes, and biogeochemical enrichment.

Moorings are currently the only viable platforms for a sustained observing system in the narrow passages where the flow is fast and sufficiently confined by the bathymetry. However, while they provide excellent time series resolution, the mooring shortcomings (potential lack of cross-channel resolution of the current structure, poor coverage of the temperature-salinity (T-S) in the upper ∼100 m of the water column because of lack of a surface expression, heavy shipping traffic) might be complemented by HF radars to provide real-time surface current measurements. Gliders, providing near-real-time measurements, could be tested for measuring the transport through the wider Solomon Strait where the currents are not accelerated by confinement in narrow channels. It is worth noting that maintaining instrumentation in such remote areas will require dedicated personnel efforts and international coordination.

North Pacific Low Latitude Western Boundary Current

The North Pacific LLWBC system originates from the bifurcation of the North Equatorial Current (NEC) near the Philippine coast, resulting in a complex and time-varying distribution of its mass and properties among the Kuroshio, MC, Mindanao Eddy (ME), and North Equatorial Counter Current (NECC) (see **Figure 5** for locations). High-salinity North Pacific Tropical

Water is redistributed north and south, with the southward MC the primary source of the ITF (e.g., Gordon and Fine, 1996). Unlike the Solomon Sea, where the western boundary flow is primarily an undercurrent (see The Southern LLWBCs: The Solomon Sea), the MC is surface-intensified with the bulk of its transport above 250 m (Wijffels et al., 1995; Schonau and Rudnick, 2017; **Figure 6**).

Opposite-direction undercurrents below both the Kuroshio and MC (e.g., **Figure 6**) converge to feed eastward subsurface jets (Qiu et al., 2013; Cravatte et al., 2017); the northward Mindanao Undercurrent also carries intermediate water from the South Pacific into the northern hemisphere (Qu and Lindstrom, 2004; **Figure 5**). Strong intraseasonal variability of these undercurrents has been identified from subsurface moorings (e.g., Wang et al., 2016). Recirculations offshore of the LLWBCs and the presence of both permanent and transient eddies complicate the understanding of current connectivity and blur the boundaries that define the LLWBC transport itself.

As is the case for the Solomon Sea (see The Southern LLWBCs: The Solomon Sea), the several possible destinations of the MC flow matter a great deal in diagnosing the downstream effects on the tropical Pacific as a whole. While one part of the MC flows directly into the ITF, an unknown amount enters the equatorial current system; since ITF transport varies strongly with ENSO (see Links to Indian Ocean: The Indonesian Seas), it is likely that this distribution changes with time. Determining the partitioning along these pathways and their variability is the key goal of observing this region.

The importance of the northern LLWBCs and their connection to the ITF has motivated several modern programs using diverse techniques to sample the region, effectively testing possible strategies for long-term monitoring. Investigators working under the Northwestern Pacific Ocean Circulation and Climate Experiment project have deployed moorings across the zonal currents east of the Philippines and spanning the bifurcation of the NEC, especially focusing on the undercurrents. Some of these sites include real-time

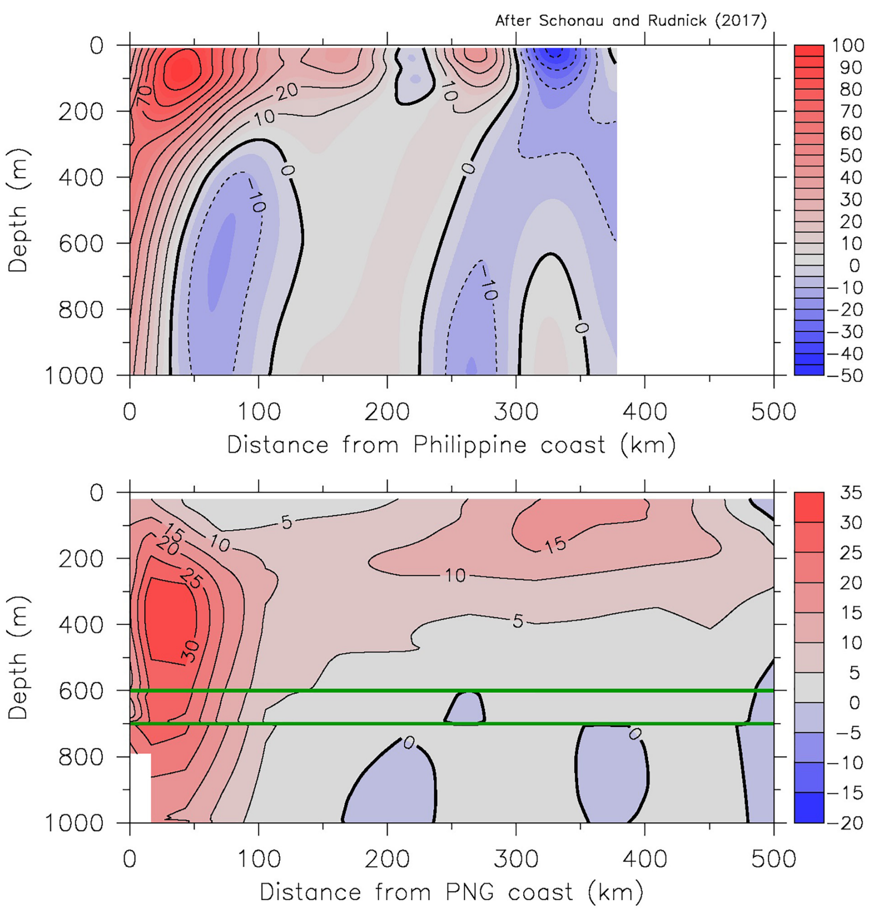

FIGURE 6 | Mean absolute geostrophic velocity on two transects across the LLWBCs of the Northern **(top)** and Southern **(bottom)** Hemispheres, from glider data. Red (positive) is equatorward in both panels, but the contour levels are different (scales in cm/s at right of each panel). The **(top)** panel is redrawn from **Figure 4** of Schonau and Rudnick (2017). The green lines in the bottom panel separate regions with different sampling periods and were contoured separately. The western boundary currents are the red areas tight to the western edge, in each case about 100 km wide; note that the northern LLWBC (Mindanao Current) is surface-intensified with its maximum above 100 m, while the southern LLWBC has its core near 400 m, and little surface expression.

data transmission. Gliders deployed under the Origins of the Kuroshio and Mindanao Currents program (Rudnick et al., 2015) produced 16 transects across the complete MC-ME-MUC system near 8°N during 2009 to 2013, measuring temperature, salinity and referenced geostrophic velocity. These allowed estimate of the mean and the seasonal and interannual variability of the system as a whole (Schonau and Rudnick, 2017; see **Figure 5**). Recently, investigators from the Korea Institute of Ocean Science and Technology (KIOST) and Inha University deployed a line of bottom Current and Pressure Recording Inverted Echo Sounders and subsurface Acoustic Doppler Current Profiler (ADCP) moorings across nearly the entire system at 8°N. While the data will not be available until the moorings are serviced, the array will provide highly resolved time series, invaluable in evaluating possibilities for sampling these currents. Although these individual research efforts have described important aspects of the variability, none have yet pointed to a sustainable monitoring strategy.

The complex flow and various pathways for the northern LLWBC, with no defined boundary to the east, make the design of a credible monitoring strategy for the MC more challenging than for either of the other two LLWBC regions. As in the case of the other LLWBC systems, the goal will be monthly resolution, and a multi-platform approach seems most appropriate. Such an approach might include a line of moorings to sample subsurface temperature and velocity, combined with Argo floats and glider transects to provide the real-time fields. A near-term goal should also investigate whether global observing programs (such as Argo combined with satellite altimetry) can produce useful estimates of the MC mass and property transport without dedicated *in situ* observations; the fact that the MC is shallow and surface-intensified makes this a realistic possibility. Two issues should be studied: First, how far offshore of the Philippine coast does Argo geostrophy give a reliable measure of the meridional currents? Second, can altimeter-derived surface velocity anomalies, combined with Argo temperature and salinity sampling, resolve the flow close to the coast? These can be tested with the present KIOST line of mooring data when those become available.

Links to Indian Ocean: The Indonesian Seas

The Maritime Continent of Indonesia forms the leaky western boundary of the equatorial Pacific Ocean. The fresher water within the upper thermocline of the Indonesian seas is primarily derived from the North Pacific LLWBC entering via the Sulawesi Sea that then mostly flows into Makassar Strait. A smaller quantity of saltier lower thermocline and intermediate waters are derived from the South Pacific LLWBC (likely originating from Vitiaz Strait) and enter via the Maluku Channel and the Halmahera Sea. The North and South Pacific water masses mix within the various basins in the Indonesian seas to form the isohaline profile that is exported into the tropical Indian Ocean and beyond.

The mean ITF transport of ∼15 Sv from the Pacific and its associated heat transport to the Indian Ocean must be accounted for to close the equatorial Pacific heat budget. The transport varies considerably on interannual to multi-decadal timescales largely associated with ENSO and Indo-Pacific decadal variability (see Sprintall et al., 2019, this issue). The flow is maintained by a pressure gradient between the Western Pacific and Eastern Indian ocean that is modulated by wind and buoyancy changes over the tropical Indo-Pacific (Wyrtki, 1987), primarily tied to variations in the strength and location of the Walker circulation, whose center of convection is located over the Indonesian Seas. Recent observations have demonstrated a large multi-decadal intensification of the ITF and its heat transport in tandem with anomalously strong Pacific trade winds (see Sprintall et al., 2014, 2019 for a review). Understanding the changes in the vertical profile of velocity is critical for understanding changes in the biogeochemical properties that are linked to changes in the behavior and species distribution of the rich ecosystems within the Indonesian seas.

At present there are only a few long-term direct measurements of the ITF within the Indonesian seas (e.g., Gordon et al., 2012; see Sprintall et al., 2019, this issue). To better understand future ITF changes and their links to the western Pacific LLWBCs and tropical Pacific, we need to develop a sustained array that measures the ITF vertical profiles of not only velocity, but also temperature, salinity and other properties. The design of a suitable monitoring array for the ITF is challenging since we do not yet have a full understanding of the various transport streams and how partitioning through the various entry and exit channels change on interannual and longer time scales. Sustained measurement within the western Pacific entrance passages are also complicated by recirculation features in the energetic Halmahera and Mindanao Retroflections (**Figure 5**) that can influence the transport of water into the Indonesian seas. In addition, near surface measurements are hampered by damage from fishing and vandalism. For these reasons, an ITF monitoring strategy for the entrance ITF channels from the Pacific might best be achieved by focusing on mooring deployments in the relatively narrow constrictions that are not influenced by recirculations (e.g., the 680 m Labani Channel in southern Makassar Strait that capture 80% of the upper thermocline Pacific inflow and the deeper 1890 m Lifamatola Passage). As in other LLWBCs, at present the moorings do not report in real-time and only resolve full-depth velocity and so additional T-S measurements, such as from long-term XBT and glider transects or Argo profiles (e.g., Wijffels et al., 2008; Sprintall et al., 2009; Gruenberg and Gordon, 2018) are needed to develop proxy measurements of heat and freshwater fluxes. The wider eastern passages of the Seram Sea have never had adequate transport resolving coverage before, but water mass observations suggest that they provide an important source of South Pacific water. Although the flows may be swift, it could be that (multiple) glider transects might offer the best strategy to obtain a transport mass, heat and freshwater time series in these eastern pathways. ITF transport proxy measurements have also been successfully derived from altimetry, Argo profiles and reanalysis data. However, this typically only gives information about the total mass transport changes.

Toward a Future Integrated Observing System for the LLWBCs and ITF

Final recommendations for designing a Pilot study able to develop an optimal sampling strategy for resolving the mass, heat, and freshwater transports of the LLWBC and ITF are given here.

- The ultimate target, as stated above, is to monitor LLWBCs heat transport to 500m at monthly/seasonal timescales. Ideally this should include simultaneous heat transport measurements in the northern and southern LLWBCs and the ITF.
- Further analyses are still needed to compare the existing different transport estimates in the northern and southern LLWBCs and in the ITF, and to determine the scales of intrinsic variability. In particular, comparisons of transport estimates at the entrance and exits of the Solomon Sea by different platforms should be planned.
- A single platform approach is not adequate, rather combining multiple and complementary platforms will be required for a sustained observing system of the LLWBCs. The ability of altimetry combined with Argo to produce useful estimates of the Mindanao mass and property transport should be investigated.
- International and regional cooperation, and dedicated personnel efforts will be necessary to sustain an observational network in these remote areas, and for coordinated data sharing.
- Monitoring the LLWBCs micronutrient content variations is currently restricted to careful ship-based measurements of iron, however, the timescales of release of iron from likely sources (river, hydrothermal, etc.) highlight the need for autonomous observing technology development. Further process studies are needed to better understand the locations and processes of the land to ocean inputs. This also requires understanding the effect of these properties on the downstream productivity and their interaction with other forcing terms. A first achievable step toward a sustained monitoring effort might be to monitor the micro-nutrients concentrations downstream in the EUC east of 156°E since this will ultimately impact the productivity of the eastern Pacific.
- In addition to these recommendations for sustained monitoring, a better understanding of the processes controlling the vigorous mixing occurring in the LLWBCs and ITF is needed. Mixing is known to be important for the transformation of water masses, but it is localized, highly variable, and difficult to estimate in these regions (Koch-Larrouy et al., 2015; Alberty et al., 2017; Bouruet-Aubertot et al., 2018; Sprintall et al., 2019); more targeted process studies are needed.

Eastern Pacific

The Eastern Pacific (EPAC) region is arguably among the most problematic in the world for climate modeling, as oceanic processes, low-cloud physics, and convective rainfall processes have complex interactions that have eluded adequate representation for several decades, contributing to severe biases in even the best of the state-of-the-art climate models (**Figure 7**). Global coupled climate models suffer in particular from the so-called double ITCZ, which refers to the strong positive rainfall biases in the southeastern Pacific throughout the year (Bellucci et al., 2010), as well as a too diffuse thermocline that weakens the thermocline feedback, a main deterministic process for El Niño development. At the southern edge of the tropical EPAC is the stratus region, where coupled models and reanalysis consistently underestimate the frequency of low cloud, resulting in overestimation of the net surface heat flux in the region (e.g., Cronin et al., 2006; de Szoeke et al., 2012). Observing the EPAC from the ITCZ through the stratus region on sub-seasonal to interannual time scales is important for resolving such long-standing issues.

Recent research also highlights the existence of two ENSO regimes, one associated with extreme El Niño events in the EPAC, and the other with moderate events centered in the Central Pacific (also called a Modoki or Warm Pool El Niño event). Such differences in the amplitude and spatial patterns of ENSO events, referred to as ENSO diversity (Capotondi et al., 2015), result from variations in the balance between the thermodynamic feedback across the equatorial Pacific and the activation of the non-linear Bjerknes feedback, when the far eastern Pacific warms above a temperature threshold corresponding to the convective threshold (Takahashi and Dewitte, 2016; Takahashi et al., 2018). Thus, monitoring the heat content in the far eastern Pacific is key for ENSO forecasting. While heat content can be approximated by the zonal average of equatorial thermocline anomalies, which the current TMA permits, it is also influenced by diabatic processes including diapycnal mixing, eddy-induced transport, and short-wave penetration (Lengaigne et al., 2012) that cannot be constrained by the observing system. In particular, the sloping thermocline induces a modal dispersion of equatorial Kelvin waves, which is associated with mixing processes that modulate heat content in the far eastern Pacific (Mosquera-Vásquez et al., 2014). Tropical instability waves also yield eddy-induced meridional heat transport that can influence the growth of ENSO (Holmes et al., 2018), while eddy-induced heat transport originating off the coast of Peru is important for the heat-budget at regional scales (Colas et al., 2012). Overall, these studies indicate that the perceived role the EPAC plays in ENSO has evolved since the era when the TMA was first implemented. The recommendations for the EPAC observing system must reflect this evolution in thinking.

Since the inception of the TMA, maintaining observations within the TMA along 95°W has been challenging due to the high exposure to vandalism and consequent loss of data. Data loss at these sites, as well as a lack of observations east of 95°W, limit our ability to pinpoint the causes of model deficiencies, despite the additional data from the Argo system and satellites (Xue et al., 2017). In particular, uncertainties in the atmospheric forcing from models in this region remain a concern for oceanic reanalysis, especially regarding their impact on regional air-sea coupled modes (Dewitte and Takahashi, 2017; Takahashi and Martínez, 2017) and their potential upscale effects on the tropical Pacific circulation (Toniazzo, 2010). Some of the main issues in atmospheric modeling of the EPAC are related to uncertainties

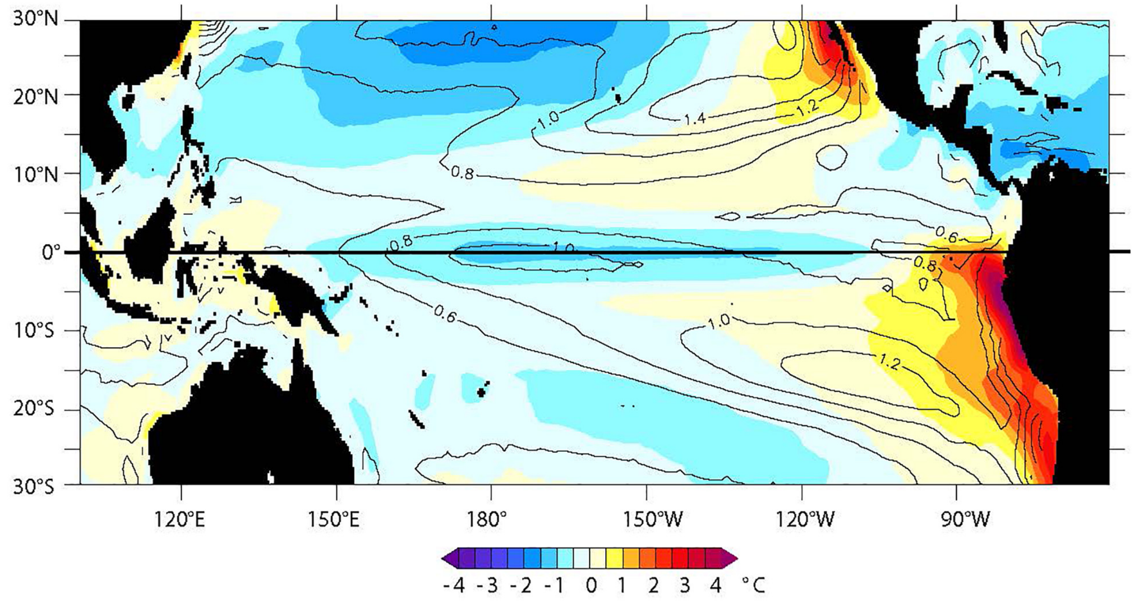

FIGURE 7 | Mean SST bias (colors) of an ensemble of 39 coupled GCMs from the CMIP5 historical experiments over 1982–2005 relative to Reynolds SST (Reynolds et al., 2007). The contours indicate the standard deviation of the mean bias amongst the model ensemble (in °C).

in the surface heat fluxes and PBL parameterizations (Tapiador et al., 2018), as well as the vertical heating structure of the EPAC ITCZ. Satellite based measurements indicate that the maximum in convective heating is in the mid-upper troposphere (Schumacher et al., 2004), but reanalysis products indicate that the ascent is shallow (Back and Bretherton, 2006), consistent with the direct observations of a strong shallow overturning circulation in this region (Zhang et al., 2004). The vertical structure of the latent heating is of particular importance to ENSO, since it has a substantial influence on the surface wind response that is key for the Bjerknes feedback (Nigam et al., 2000; Nigam and Chung, 2000; Wu, 2003). In addition, the coupling between the ITCZ and SST provides non-linear feedbacks into the ENSO system (Dommenget et al., 2012; Lloyd et al., 2012; Takahashi and Dewitte, 2016).

The far EPAC also contains the most productive oceanic ecosystems in the world, and many livelihoods depend on a variety of marine resources that contribute significantly to local and international economies, as well as local cultures (Chavez et al., 2014). This relatively high biological productivity associated with the sluggish circulation in the subthermocline means the EPAC hosts the most extended OMZ in the world (Paulmier and Ruiz-Pino, 2009), important to climate feedbacks through the release of potent greenhouse gasses (see Biogeochemistry and Ecosystem Contributions). While open ocean deoxygenation during the second half of the 20th century (Breitburg et al., 2018) represents a threat to the marine ecosystems of the EPAC, the forcing mechanisms of the OMZ remain poorly known (Oschlies et al., 2017), mostly because oxygen data are very scarce and the transport of oxygenated waters by the equatorial undercurrent to the coast at subsurface is through fine meridional scale zonal jets (i.e., Tsuchiya jets) (Montes et al., 2014), poorly simulated by global models. The extension of the observing system to the far EPAC thus offers an opportunity to monitor key biological parameters (e.g., O_2 and fluorescence) for improving our understanding of the OMZ dynamics.

Further progress in our understanding of the mechanisms governing climate variability and predictability in the EPAC and of its impacts, including ENSO, requires enhanced observing capabilities in this region, through a combination of existing technologies (i.e., Argo floats, satellite observations, autonomous vehicles) and appropriate network design (e.g., Cravatte et al., 2016). In particular, this new design will need to consider the coastal transition zone (coastal upwelling system), equatorial upper ocean non-linear processes, the vertical structure of the ITCZ and associated air-sea fluxes, the OMZ (Takahashi et al., 2014), and external ENSO forcing such as the South Pacific Meridional Mode (SPMM: Zhang et al., 2014) that can modulate the amplitude of ENSO (Larson et al., 2018).

To this end, the existing TMA line along 95°W should be maintained and expansions of the TMA into the northeast Pacific ITCZ and seasonal southeast Pacific ITCZ are necessary. Oceanic and biological conditions in the coastal regions of the EPAC are monitored by the countries along the west coast of South America for ecosystem management. However, there is currently no regional coordination in the framework of TPOS 2020, although the Permanent Commission for the South Pacific coordinated several annual cruises for El Niño monitoring and the GOOS Regional Alliance for the southeast Pacific (GRASP) provides a framework for data sharing. Such coordination would represent a significant advance for the observing system in the EPAC.

The Argo network is another key component of the observing system in this region, although this would require participation by all South American countries to meet the objective of doubling the density of coverage. Argo floats combined with satellite data (SST, altimetry) will address some of the knowledge gap by providing measurements of variability in upper ocean vertical structure. However, the Argo network does not allow monitoring of subsurface mesoscale ocean variability over a region due to its irregular sampling. Thus, regular hydrographic sections from ships or autonomous vehicles operated by national institutions in South America would represent an important contribution to the observing system. A section between the Galapagos islands and Ecuador or northern Peru would allow complementary measurements as well as monitor oxygen conditions and transport of water mass properties by the zonal jets to the Peru-Chile undercurrent, the conduit by which the OMZ is influenced by the equatorial variability (Montes et al., 2014). The monitoring of the coastal upwelling conditions (temperature, salinity, current and O_2 profiles at historical sections) would also allow detection of intraseasonal Kelvin waves and validate the assimilation products from these independent observations. Such monitoring is now done by national institutions in South America; thus, its implementation within TPOS 2020 would require regional coordination for sharing data and standardized protocols for making measurements.

The requirement to characterize the atmospheric state within the ITCZ, atmospheric meridional circulation across the equator and surface forcing under the stratocumulus cloud deck on monthly timescales in the EPAC, needed to validate atmospheric structure in models across seasons and during ENSO, could be met through the instrumentation of new sites associated with well-located islands, including:

Clipperton (10°18′N 109°13′W, France) and Galapagos (Ecuador) Islands: Monitoring vertical profiles of atmospheric temperature, humidity and winds during the seasonal migration of the ITCZ to obtain the vertical atmospheric structure in the region on intra-seasonal to seasonal time scales. Over longer time periods, monitoring of vertical structure over the Galapagos Islands during El Niño events (see Huaman and Takahashi, 2016) would enable better understanding of the processes associated with the non-linear amplification of the Bjerknes feedback.

Hormigas island (11°58′S 77°46′W, Peru): This small island is located 30 miles from the coast in the blind zone of satellite scatterometers (Astudillo et al., 2017). This site would allow monitoring of changes in winds along the coast of Peru that are not seen by satellites. This, in turn, will allow better understanding of coastal upwelling dynamics through estimate of the near-shore decrease of the winds (i.e., wind curl) and air-sea interactions along the coast of Peru, thought to play a role on the evolution of EPAC El Niño (Dewitte and Takahashi, 2017) and the development of coastal El Niño events (Takahashi and Martínez, 2017).

St Felix Islands of the Desventuradas Archipelago (26°17′S 80°06′W, Chile), along with the existing OceanSITES Stratus mooring (20°S, 85°W), are ideally located for monitoring the stratocumulus cloud deck, important for moderating local SST and surface buoyancy forcing, as well as being a key region for understanding the interhemispheric surface energy balance important to the seasonal double ITCZ in the eastern Pacific (Kang et al., 2008, 2009; Li and Xie, 2014; Zhang et al., 2015). This site is also well located for monitoring the SPMM.

In summary, the EPAC design should include:

- The ability to capture intraseasonal to interannual variability in the coastal transition zone;
- Improved observation of equatorial upper ocean non-linear processes on intraseasonal time scales;
- Observations of atmospheric vertical structure within the ITCZ and associated air-sea fluxes;
- Observations of the OMZ and associated advection of oxygen by the surface and sub-surface current systems of the EPAC; and
- Capability to monitor modes of external ENSO forcing such as the South Pacific Meridional Mode.

TRENDS IN TECHNOLOGY AND SAMPLING TECHNIQUES

While the TPOS backbone must rely upon proven technology, with systematic engineering and development and pilot studies, it is possible for new technologies to transition through multiple Technical Readiness Levels (TRL) (Lindstrom et al., 2012). With this in mind, we see a number of trends in technology and sampling techniques that may be ready to adopt into the TPOS backbone in the next decade.

New Sensors

One of the great legacies of OceanObs'99 was the initiation of the Argo float array (Argo Science Team, 1999). Ten years later, a legacy of OceanObs'09 was the consensus that these platforms should serve multidisciplinary functions. This has led to the development of a global BGC-Argo community (Claustre et al., 2010; Gruber et al., 2010)[1] with miniaturization of numerous sensors previously used only within carefully controlled shipboard experiments. Among these biogeochemical enhancements, oxygen measurements have the longest history, but through several large research programs, most notably SOCCOM[2], a standard suite of biogeochemical parameters is emerging. These are temperature, salinity, dissolved oxygen, pH, nitrate, chlorophyll fluorescence, particulate backscatter, and downwelling irradiance. More than 100 such floats have been deployed in the Southern Ocean but tropical Pacific deployments remain scarce.

Acoustic-based sensors of physical measurements also show great promise. Measuring wind and rain from passive aquatic listening device below the ocean surface could have the advantage of avoiding detection from the fishing fleet and thus having reduced data loss from vandalism. Likewise, depending upon the depth of the sensor, the footprint of the acoustic signal may be 100's of meters in radius and therefore may be more comparable to a satellite footprint than a buoy point measurement.

[1] http://biogeochemical-argo.org/

[2] https://soccom.princeton.edu/

New sensors are also being developed for satellite applications. As described by Villas Bôas et al. (2019), both NASA and ESA are developing potential sensors for satellite application that could measure wave height and surface currents from a single sensor. These are presently at a prototype TRL, with field tests from aircraft, but by 2030 may be operational. If so, this could play an important role, filling a gap in the surface current observing capabilities of the TPOS. Because currents at the equator are strongly ageostrophic, relying upon geostrophic methods for computing currents introduces large errors. Direct measurements of currents are needed for TPOS and the capability of doing so from space adds important spatial coverage and horizontal resolution capability.

Autonomous Vehicles and Adaptive Sampling Strategies

An exciting new trend in technology is the growth of autonomous vehicles: underwater gliders, autonomous surface vehicles (e.g., Wave Gliders and Saildrone), and airborne drones. Unlike floats, drifters and radiosondes, autonomous vehicles can be navigated by a pilot. Surface EOV and ECVs that have been observed from autonomous surface vehicles include wind speed and direction, wind stress, air temperature and humidity, solar and longwave radiation, barometric pressure, air and sea pCO_2, SST, SSS, Chl, O_2, and upper ocean velocity. For many of these vehicles, the endurance is sufficiently long – several months or even approaching a year – it is more efficient to have the pilot shore-based, even if the vehicle is deployed and recovered from a ship. However, for many of the applications and for some vehicles like Saildrone, the autonomous surface vehicle can travel thousands of kilometers and thus can be deployed and recovered from a seaside port, rather than a ship. In general, autonomous vehicles rely upon aerodynamics for propulsion from wind, waves, or buoyancy. As the impacts of anthropogenic global warming begin to increase, these fossil-free solutions for observing the climate will become more and more important.

While autonomous vehicles can potentially hold station, much like moorings, an important advantage of these vehicles is that they can be navigated. Thus they can perform repeat sections and surveys, which can adapt to conditions at hand. For example, these vehicles may provide an alternative to TPOS moorings in high vandalism regions and could provide surface EOV and ECV along transects previously monitored by TMA moorings and the mooring tender research vessel. They also may focus on fronts between different regimes, such as the front that separates the equatorial "cold tongue" from the warm water to the north (and south) where ITCZs and convection form. Likewise, the vehicles may focus on the front of the eastern edge of the equatorial Pacific warm pool. During El Niño, this front shifts eastward so that warm water extends across much of the equatorial Pacific.

With the strong currents and weak winds and waves found in the tropics, the tropical environment is a surprisingly difficult environment for autonomous vehicles. To become effective components of the TPOS backbone, these new technologies must continue to be tested in the field and in the operational environment. Doing so may have enormous payoff for the TPOS in added capability, efficiency and resilience.

PHASED CHANGES TO THE BACKBONE

We envisage a staged implementation of the new Backbone with ongoing assessment through to full maturity. Many elements are connected through to global systems and will evolve accordingly, but with recognition of and advocacy from the TPOS community (users, sponsors, research). Others will require specific actions from the TPOS community and these are discussed in more detail below.

Figure 8 shows an assessment and a projection of the status of TPOS measured against requirements at the EOV level (see **Figure 1**). For SST, SSH and ocean color the situation and future prospects are strong. Increased assurance for passive microwave measurements of SST is desired, and the *in situ* networks need future improvement. The requirements for wind are being met adequately, but as noted in Section "Recommendations for an Integrated Backbone," at least one more scatterometer is required to achieve the desired coverage. The First Report highlighted areas for improvement in the *in situ* vector wind record over the coming 5 years. SSS has benefited from experimental satellite missions during the last decade but these are expected to cease during the coming 3–5 years. The quality of SSS retrievals now fully justify a follow-on mission(s) and TPOS will argue for this in its 2nd Report. The situation for flux variables remains marginal with a strong reliance on high-quality *in situ* data; there are prospects for improving this situation as reflected in the figure. TPOS is advocating improvements for subsurface temperature and salinity with the prospect of both reaching the adequate level or better by 2025. Surface and subsurface ocean velocity requirements are considerably more difficult to satisfy. Remote measurements are being planned (see Trends in Technology and Sampling Techniques) and provide some potential for meeting needs at the surface at least. The First Report identifies actions to strengthen subsurface *in situ* sampling. Surface seawater pCO_2 relies on sparsely distributed *in situ* networks (marginal) but BGC-Argo may be a game changer for subsurface biogeochemical processes. Ocean surface precipitation remains at the marginal to good range, principally due to the uncertain representativeness of buoy point measurements of rainfall.

A possible transition timing is shown in **Figure 9** with most activities beginning in 2019–2020, and serious implementation and change spread over 2020–2023. Note that this schedule is only indicative since there are many variables in the implementation that are currently unresolved. In this schema, full implementation would not be achieved until 2024. The transition rate is resource dependent, but a steady and slower implementation allows assessment of the changes to occur, and particularly allows learnings on the use of new platforms and sensors.

For Argo, the deployment rates per year (over current numbers) will depend on the residence time in the tropics and the western and eastern Pacific in particular; the deployment strategy will have dual goals of maintaining the core Argo distribution

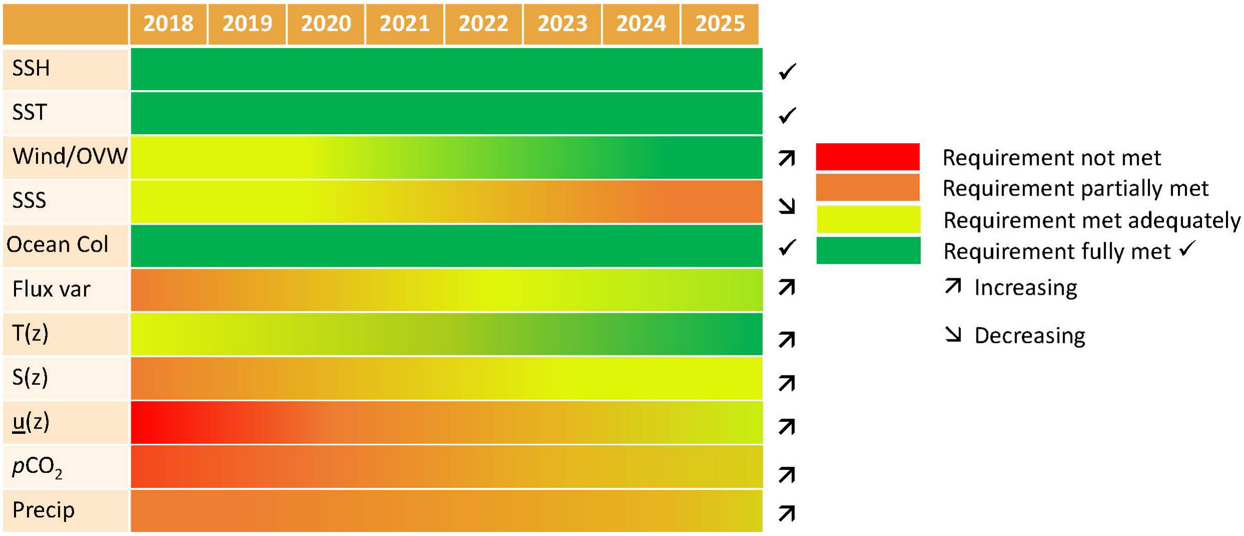

FIGURE 8 | Status of the observing system in the tropical Pacific with respect to the main variables and requirements as set out in Section 3.4 of Cravatte et al. (2016). The variables are SST, sea surface height (SSH), wind/ocean vector wind, SSS, ocean color, heat and freshwater flux, vertical temperature, salinity and velocity, pCO_2 and precipitation. The assessment of status is broad and not at the detailed level. The four status levels are (a) red: requirement not met or only in part; (b) gold: requirement partially met (useful/threshold in the language of WMO Rolling Review of Requirements http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html); (c) lime: requirement met adequately (breakthrough); and (d) green: fully met or exceeded (ideal/goal).

Partially met Met adequately

<table>
<tr><th></th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th></tr>
<tr><td>2x Argo (west)</td><td>10</td><td>30</td><td>30 ||</td><td>30</td><td></td><td></td><td></td><td></td></tr>
<tr><td>TMA west</td><td></td><td>℗ ||</td><td>+4</td><td>+4</td><td>Full "丁"</td><td></td><td></td><td></td></tr>
<tr><td>Full flux</td><td></td><td>℗ ||</td><td>50%</td><td>100%</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Argo Δz</td><td>25%</td><td>50%</td><td>75%</td><td>100%</td><td></td><td></td><td></td><td></td></tr>
<tr><td>TMA Δz, u(z)</td><td>℗</td><td>℗ ||</td><td>+3</td><td>+3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>ΔTMA</td><td></td><td></td><td>Δ1 ||</td><td>Δ2 ||</td><td>Δ3 ||</td><td></td><td></td><td></td></tr>
<tr><td>TMA 1° 140W</td><td>℗</td><td>℗ ||</td><td>+2</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2x Argo (east)</td><td></td><td>15</td><td>15</td><td>15 ||</td><td>15</td><td></td><td></td><td></td></tr>
<tr><td>TMA *2</td><td>1||</td><td>2||</td><td>2||</td><td>3||</td><td>3||</td><td>3||</td><td>3||</td><td>3||</td></tr>
<tr><td>2x Argo (rest)</td><td></td><td></td><td>40</td><td>40</td><td>40</td><td>40</td><td></td><td></td></tr>
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FIGURE 9 | Schematic providing detail of the schedule for change in the Backbone involving Argo, the TMA, and so-called super-sites (here denoted by TMA*2). The symbol Ⓟ denotes a pilot mode. The symbol | | refers to review/evaluate points. For Argo the numbers show the annual seeding rate. For the TMA the numbers usually refer to enhancement levels. In anticipation of changes to the TMA (denoted by ΔTMA), we assume three phases Δ^1, Δ^2, and Δ^3, following the priorities outlined in Section "The TPOS 2020 First Report." The shading indicates the degree to which requirements will be met through this schedule (approximate) except for the supersites. "TMA west" currently consists of the TAO line at 165°E and 3 JAMSTEC sites. The former State Oceanic Administration have outlined plans to develop the so-called "ding" array (denoted by "丁") which extends the TMA to the northwest while at the same time supporting some of the key equatorial sites of the TMA (Chen et al., 2018).

while at the same time achieving the TPOS enhancement. We assume that around 30% of all enhancements will be BGC-Argo floats. The priority is in the order shown. Increased vertical sampling (Argo Δz) is already underway with Argo's use of high bandwidth satellite communications in new floats.

The schedule for enhancing the western Pacific part of the TMA is initially dependent on Chinese plans for the so-called "Ding" array ("丁"), that will implement broader western Pacific coverage to enhance observations of the Warm Pool, Asian Monsoon, western boundary currents, and for typhoons

(Chen et al., 2018). Here we assume a pilot will be deployed in 2019 (for cross-calibration and testing) and that the full array will follow over 3–4 years. We also assume JAMSTEC will continue to occupy three sites, including a super-site (see below). This 'TMA west' schedule will deliver partial restoration of the core equatorial TMA (4 out of 7) and enhancements in the northwest which will be discussed in the 2nd Report of the TPOS 2020 Project.

Several sensor and platform configurations required for the TPOS 2020 Backbone are currently being trialed (pilot experiments), including improved vertical sampling of currents (TMA Δz); subject to positive evaluation these will be implemented at the equatorial mooring sites. The proposed 1°N/S enhancements to the TMA at 140°W (see the First Report) also fall into this category, but long-term implementation has some dependency on the TMA reconfiguration (ΔTMA).

The "full flux at all moorings" recommendation (see Air-Sea Interface Surface Variables and **Figure 3**) involves a largely proven approach but we expect it will be prudent to phase this change in so that assessment and evaluation can take place. As noted in the First Report, this change does not require a significant injection of resources, but it is nevertheless of a scale that will require careful planning and coordination, including for data management needs. The roll-out should begin with the established TMA sites before new sites are instrumented.

The transformation of the TMA (assumed to be in three phases Δ^1, Δ^2, and Δ^3) will undoubtedly pose the greatest challenge since it will be undertaken in an environment where resources are a strong consideration and full implementation requires coordination and cooperation between three or more agencies (see discussion in Section "The Rationale Behind the Reconfiguration of the Backbone"). The changes should be staged, and review and assessment should accompany each stage (denoted in the figure by ||). Sensitivity studies should be conducted to test the assumptions behind the design and to evaluate any anticipated impact. However, it should be noted that any such study will not be conclusive since the studies themselves are impacted by assumptions and parameterizations, and sensitivity experiments often have to be interpreted in the presence of significant systematic errors (see Fujii et al., 2019, for a fuller discussion).

The TPOS 2020 Project is currently considering options at the detailed level, such as the preferred longitudes and latitudes for extensions, and any priorities within the extensions themselves.

In addition to these Backbone changes, several so-called TMA supersites have been proposed (denoted TMA^{*2}). At these sites direct covariance flux measurements (DCFS) may be trialed, as well as new approaches such as hygrometers and infrared radiometers (for true satellite SST validation). They also provide opportunity to trial biogeochemistry and biological sensors.

To help work through the inevitable challenges these data streams will present and to assess their efficacy and refine their costings, pilots and improved technical coordination among those supporting TPOS are required. The pilots should be implemented as soon as possible, and indeed some of them have already began, as noted above. The outcomes from pilots should be assessed and shared regularly across the TPOS implementation teams and user groups. In addition, to ensure uniform data quality, sharing of technical and data processing practices across implementing teams is also required, and needs to be established where this does not exist.

A set of process studies have been proposed to aid the design and the evolution of TPOS (see the First Report, Chapter 6). Some of these studies have been initiated, some are close to completion, while others await investment. All are important for the phased implementation and improvement of TPOS. Section "Biogeochemistry and Ecosystem Contributions" refers to biogeochemical studies that are important for the design of that component of the observing system, some parts of which are underway. Section "Eastern Pacific" makes the case for an East Pacific ITCZ/warm pool/cold tongue/stratus system study. A Pacific upwelling and mixing physics process study aims to understand the complex of processes connecting the thermocline and the surface in the eastern equatorial upwelling region that is a principal control on SST and thus enables the large-scale air-sea feedbacks crucial to ENSO. The National Oceanic and Atmospheric Administration has funded the initial work on this study, including modeling. Two air-sea interaction studies (northern and eastern edge of the Warm Pool) have been the subject of initial exploratory work but are still to be initiated as a coherent and coordinated piece of work.

Assessments are a crucial activity as pilots transition to full implementation and changes are undertaken, to help quickly diagnose issues and feed them back to the implementing teams. It is unlikely we will have the luxury of mandating overlapping periods, but to the extent possible change will be in accordance with GCOS Monitoring Principles (Global Climate Observing System [GCOS], 2010). Fujii et al. (2019) provide several examples of how such work might be done, but it will also be important that future governance arrangements take this need into account, including the need for ongoing oversight (see the following section).

TPOS GOVERNANCE AND PARTNERSHIPS: SUSTAINABILITY

The TPOS 2020 Project effectively takes the design and support of the TPOS "offline" from global governance (that is, not directly coordinated by) to undertake reevaluation of the requirements and the design, and to begin the process of change to achieve a more effective and efficient system. The TPOS 2020 Steering Committee is responsible for scientific and technical aspects, while the Resource Forum provides representation for stakeholders (user, providers, beneficiaries); see **figure 10**. TPOS 2020 has a fixed-term and deploys standard project management techniques to support its activities.

At the creation of the Project, there was no dedicated governance arrangement for the TPOS; some elements fell within the responsibilities of the Joint WMO/Intergovernmental Oceanographic Commission Technical Commission for Oceanography and Marine Meteorology (JCOMM) and its Observation Program Area (e.g., drifters, ships of opportunity) while others, such as Argo, enjoyed independent governance

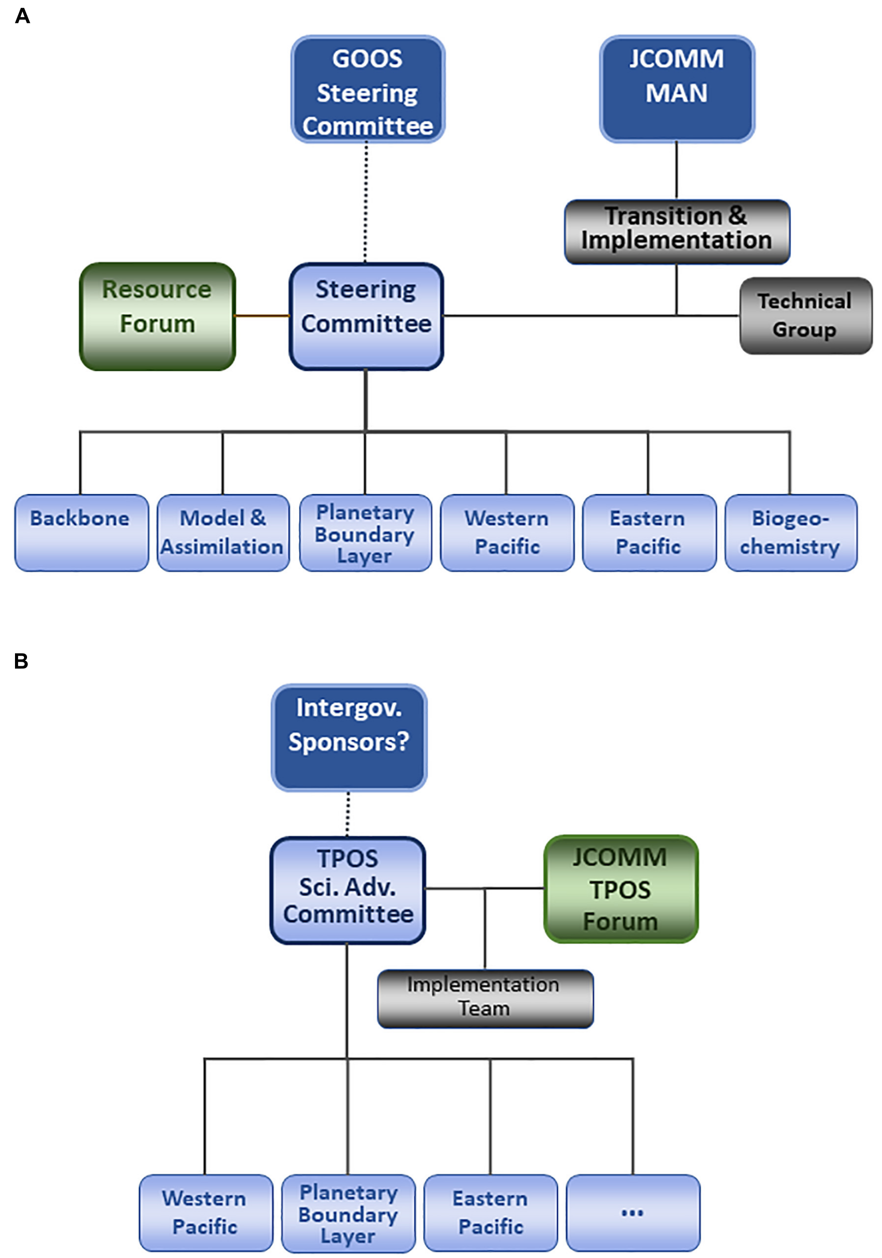

FIGURE 10 | (A) TPOS 2020 Project governance arrangements. The TPOS 2020 Steering Committee has six Task Teams (as shown) and shares a seventh (the Transition and Implementation Task Team) with the JCOMM Management Group. The Resource Forum is a key element of the structure. Further details are available from tpos2020.org. **(B)** Possible post-2020 TPOS arrangements. It is likely a science/steering committee will continue and that at least some of the Task Teams will have renewed mandates. A regional TPOS Forum is proposed to facilitate coordination and cooperation between partners, and with users/beneficiaries.

arrangements but otherwise were fully coordinated with JCOMM. The Tropical Mooring Implementation Panel (TIP[3]), which provided the original oversight and scientific and technical leadership for TAO/TRITON now falls within the Data Buoy Cooperation Panel of JCOMM and in principle retains the intergovernmental lead for the global TMA. The TIP were among the first to draw attention to the deterioration of the TMA in 2012/2013, however, as the events unfolded during that period it was clear TPOS lacked coordination among the network providers and active oversight and management of risk was lacking (Global Climate Observing System [GCOS], 2014a,b).

At the most recent meeting of the Resource Forum[4], each of the 14 participating organizations expressed strong support for the TPOS 2020 plans and recognized the need for strong and

[3] https://www.pmel.noaa.gov/tao/proj_over/tip/newpanel.html

[4] http://tpos2020.org/

effective future coordination. The Forum supported the TPOS 2020 First Report and its specific short- and near-term actions, noting that they will benefit the strategic goals for TPOS, the global ocean observing community and decision makers who rely on knowledge of the tropical Pacific for livelihoods, public safety, and commerce. The Forum supported the establishment of a task team to guide implementation of the recommendations and actions.

Given the importance of the Tropical Pacific for the provision of seasonal-interannual predictions, and the importance of strengthened engagement with Meteorological Services in the future of the observing system, it was important to engage JCOMM, and WMO through the WMO Integrated Global Observing System (WIGOS) in discussions on future governance. The implementation task team, now known as the TPOS/JCOMM Transition and Implementation Task Team (T&I TT) (**Figure 10A**), is an early manifestation of the type of coordination and cooperation that will be needed for maintenance of the TPOS in the future. WMO WIGOS recognizes the activities of the T&I TT as a regional Pilot and the joint sponsorship by JCOMM is an acknowledgment by JCOMM that such coordination might be needed in the post-TPOS 2020 era (see the decision in World Meteorological Organization [WMO], 2017). Discussion of post-2020 governance arrangements have commenced and must consider scientific and technical oversight and leadership (the legacy of the Steering Committee) as well as regional coordination, as discussed above. Strengthened regional coordination approaches are also being considered in other regions (e.g., the Atlantic Blueprint process, the Southern Ocean Observing System); and a number of approaches will probably be tested, to address particular scientific and geopolitical contexts.

A central theme in the governance discussions in the Tropical Pacific (and other regions) is that active and mutually supportive partnerships among TPOS stakeholders are vital for its robustness and sustainability. The TMA was put at risk in 2012–2013 because such partnerships were not in place or effective. This paper proposes that it be in the form of a TPOS Forum where partners (providers of observing capability) and users/beneficiaries can assist JCOMM in coordination and evolution of the TPOS (**Figure 10B**). It is further proposed that the TPOS 2020 (project) Steering Committee be replaced by a TPOS Scientific Advisory Committee, advising the TPOS Forum and other sponsors (e.g., GOOS and/or the World Climate Research Program) of the evolving scientific requirements (for example EOV and observing system requirements) and assessing potential technical solutions (options among the mix of platforms).

As Section "Phased Changes to the Backbone" notes, there is also a role for a TPOS Scientific Advisory Committee in the review and assessment of implementation post 2020, and in providing adjustments to strategy and/or the design as a consequence of these reviews, as appropriate.

While it is best to assess the need for scientific and technical task teams post-2020, our expectation based on the current level and expected duration of scientific activities is that some of the existing teams may continue (but perhaps with revised mandates) while others may be created. Further discussion with the scientific community will be needed to finalize the best and most efficient arrangement.

DISCUSSION AND CONCLUSION

TPOS 2020 has undertaken pioneering work on observing design, including elaboration of the Framework for Ocean Observing process. The TPOS 2020 process delineates the different steps of requirement assessment, from users through to the observing system itself. This process together with the goals agreed for the TPOS 2020 Backbone provide the framing for the TPOS 2020 First Report and for priority setting. The significant sustained (operational) use for climate prediction is one of the primary factors.

The TPOS 2020 Report builds on the strengths of the observing system, including many new capabilities that have become available over recent decades. We present a combination of enhancements and changes that play to the strengths of different observing techniques, both remote and *in situ*, to provide robustness, reinforcement and cross-checking, and greater overall resilience.

A new Backbone is outlined that enhances our capability to track long-term change, but also delivers unprecedented *in situ* observations of surface fluxes and velocity, equatorial currents and subsurface hydrography, along with robust and better validated satellite data streams. Further enhancements to capture the diurnal cycle of ocean and atmosphere coupling are also being considered.

Biogeochemistry, low-latitude western boundary currents and the Eastern Pacific are highlighted as three areas for future evolution and change in TPOS. The major biogeochemical requirements relate to the climate record of air-sea CO_2 flux, and to seasonal to interannual water column variability of inorganic carbon, oxygen, chlorophyll, particles, and nutrients. BGC-Argo observations have the potential to respond to many of these requirements.

We present a roadmap for a future integrated observing system for the LLWBCs and ITF, in the form of design elements for a Pilot study that will provide guidance on the optimal sampling strategy for resolving the mass, heat, and freshwater transports. The ultimate target is to routinely monitor LLWBCs heat transport to 500 m at monthly-to-seasonal timescales, ideally including simultaneous heat transport measurements in the northern and southern extensions of LLWBCs and the ITF. Such an approach will require international cooperation and collaboration and involve multiple and complementary platforms, such as Argo and altimetry.

It is now clear that further progress in our understanding of the mechanisms governing climate variability and predictability in the eastern Pacific, including ENSO, requires enhanced observing capabilities, through a combination of existing technologies (i.e., Argo floats, satellite observations, autonomous vehicles) and appropriate network design. This design will need to consider the coastal transition zone (coastal upwelling system), the vertical structure of the ITCZ and associated air-sea fluxes, and the OMZ. Regular sections between the Galapagos Islands and Ecuador or northern Peru would be a valuable contribution, but enhanced cooperation and data sharing will be needed. The need to characterize the atmospheric vertical structure in the ITCZ and in the stratocumulus cloud deck could be met through the instrumentation of new ocean sites on well-located islands.

We examined the status of important elements of TPOS and identified good prospects for altimetry, SST, ocean color and wind. SSS and rainfall require development and we support experimental missions to measure ocean surface currents from space. An initial timetable for implementation was provided, but subject to further discussion with the sponsors of the observing system. We contend that change in the observing system is a healthy and necessary part of the design and for maintaining engagement and investment.

This paper does not address aspects such as modeling and data assimilation, air-sea fluxes, data management or subseasonal variability. These topics are discussed in detail elsewhere in this issue. Coupled data assimilation and prediction looms as one the major developments over the next decade; already coupled numerical weather prediction and reanalysis systems are reaching into the traditional domains of oceanography. The input requirements on these shorter time scales are unknown but the First Report anticipated greater demands for upper ocean and atmosphere/ocean boundary layer data. The priority attached to the climate record has been one of the more controversial aspects of the TPOS 2020, with views ranging from fully embracing an integrated and multi-faceted and changing set of inputs to the climate record, to views that see existing data records as sacrosanct and not to be changed under any circumstances. This paper argues for a middle ground where climate records are valued, but change is also embraced.

Persistent systematic errors and difference in some data-based products and in models and reanalyses remain a point of significant concern. The power of the observing system is reduced by such factors, often in a significant and compromising way. Such issues will be a focus for the 2nd Report. Data sharing and adherence to the FAIR Principles (see Tanhua et al., 2019, this issue) are also major concerns, with many data having restricted usage.

Modeling and data assimilation systems are also an important tool for understanding the effectiveness (impact) of observations and for testing and evaluating changes to the observing system. As noted in Cravatte et al. (2016) (and reviewed in Fujii et al., 2019) observing system sensitivity and simulation experiments can provide guidance on the relative impact of (for example) moorings, floats and satellites on ocean state estimates (analyses) and forecasts. Chapter 6 of the First Report discussed some possible avenues for experimentation, however, we note such guidance is sensitive to the details of the modeling/assimilation systems and can be compromised by systematic errors.

The governance of the TPOS 2020 Project has broken new ground. The sponsors agreed to review and redesign the observing system through a project of their own creation and under their own support. The governance follows common Project Management arrangements but is somewhat unusual in the intergovernmental world, for example for GOOS, JCOMM and the World Climate Research Program. It is, however, a *modus operandi* that is often used to support space missions. The experience from TPOS 2020 suggests such approaches should be more widely used for ocean observations.

AUTHOR CONTRIBUTIONS

NS, WK, SC, JS, SW, MC, AS, and YS contributed text, review and revisions to all sections of the paper. BD and YS led the Eastern Pacific discussion and contributed review. KT provided input to and review of the Eastern Pacific section. AS led the biogeochemistry contribution with input from PS. KH contributed to the opening sections and the section on governance. AS and XL contributed to the low-latitude western boundary current section. DC contributed to Sections "The TPOS 2020 First Report" and "Phased Changes to the Backbone." SB contributed comments, review and editing.

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Developing Autonomous Observing Systems for Micronutrient Trace Metals

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Trace metal micronutrients are integral to the functioning of marine ecosystems and the export of particulate carbon to the deep ocean. Although much progress has been made in mapping the distributions of metal micronutrients throughout the ocean over the last 30 years, there remain information gaps, most notable during seasonal transitions and in remote regions. The next challenge is to develop *in situ* sensing technologies necessary to capture the spatial and temporal variabilities of micronutrients characterized with short residence times, highly variable source terms, and sub-nanomolar concentrations in open ocean settings. Such an effort will allow investigation of the biogeochemical processes at the necessary resolution to constrain fluxes, residence times, and the biological and chemical responses to varying metal inputs in a changing ocean. Here, we discuss the current state of the art and analytical challenges associated with metal micronutrient determinations and highlight existing and emerging technologies, namely *in situ* chemical analyzers, electrochemical sensors, passive preconcentration samplers, and autonomous trace metal clean samplers, which could form the basis of autonomous observing systems for trace metals within the next decade. We suggest that several existing assets can already be deployed in regions of enhanced metal concentrations and argue that, upon further development, a combination of wet chemical analyzers with electrochemical sensors may provide the best compromise between analytical precision, detection limits, metal speciation, and longevity for autonomous open ocean determinations. To meet this goal, resources must be invested to: (1) improve the sensitivity of existing sensors including the development of novel chemical assays; (2) reduce sensor size and power requirements; (3) develop an open-source "Do-It-Yourself" infrastructure to facilitate sensor development, uptake by end-users and foster a mechanism by which scientists can rapidly adapt commercially available technologies to *in situ* applications; and (4) develop a community-led standardized protocol to demonstrate the endurance and comparability of *in situ* sensor data with established techniques. Such a vision will be best served through ongoing collaborations between trace metal geochemists, analytical chemists, the engineering community, and commercial partners, which will accelerate the delivery of new technologies for *in situ* metal sensing in the decade following OceanObs'19.

Keywords: trace metals, micronutrients, *in situ* chemical analyzers, *in situ* sensors, GEOTRACES, OceanObs'19, ocean observing time series

INTRODUCTION

Bioactive micronutrient metals are essential for cell functions and mediate vital biochemical reactions by acting as cofactors in many enzymes and as centers to stabilize enzymes and protein structures (Sunda, 2012). These micronutrients – cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), zinc (Zn), and to a lesser extent cadmium (Cd) – are thus required for marine life, but can hinder cell growth at higher concentrations (e.g., through anthropogenic inputs in coastal regions). Since phytoplankton species have different cellular metal requirements (e.g., Ho et al., 2003; Twining and Baines, 2013), the supply and concentration of metal micronutrients in the ocean affects the growth and turnover rate of phytoplankton, and modulates phytoplankton species composition. The distribution of metal micronutrients ultimately influences the productivity of entire food webs and the rate of particulate carbon export to the deep ocean.

Over the past 30 years, from the pioneering work of John Martin on Fe limitation (Martin and Fitzwater, 1988; Martin and Gordon, 1988) to the ongoing GEOTRACES program that is mapping the distributions and investigating the biogeochemistry of trace elements and their isotopes throughout the ocean (Schlitzer et al., 2018), the database of discrete observations for Fe and other bioactive trace metals has grown by three orders of magnitude and encompasses observations in all ocean basins (Tagliabue et al., 2017 and references therein). These sampling efforts have greatly improved our understanding of micronutrient cycling, but are not sufficient to constrain the key processes underpinning metal micronutrient cycling and associated biological responses. For instance, Fe currently has the highest spatial and temporal observational coverage relative to all other metal micronutrients; however, **Figure 1** illustrates that even for Fe there remains large spatial gaps along with poor temporal resolution. Ship-based sampling campaigns only provide a one-time snapshot of distributions in logistically accessible regions. However, micronutrients are generally characterized by short residence times and highly variable inputs in space and time (Tagliabue et al., 2017 and references therein). As a result, the external fluxes, removal rates, internal cycling, and residence times of bioactive trace metals remain poorly constrained and their spatial and temporal variability incompletely characterized, particularly in remote regions of the oceans. This lack of understanding cascades into an incomplete representation of ocean Fe cycling in the global models used to project the impacts of change in Fe-limited regions (Tagliabue et al., 2016).

Metal micronutrients enter the ocean through a variety of highly episodic sources, including atmospheric deposition, sediment–water exchange at the land–ocean interface and intermittent venting from hydrothermal vents, which supply both metals and metal-binding ligands to the deep ocean. Metal concentrations have been observed to vary from days to months as a result of the passage of mesoscale eddies (Fitzsimmons et al., 2015), changes in mixed-layer depth via wind-driven mixing (Nishioka et al., 2007, 2011), coastal upwelling (Elrod et al., 2008), and seasonal fluctuations in dust and associated wet deposition (Boyle et al., 2005; Sedwick et al., 2005). The biological response to changing metal micronutrient distributions is also highly dynamic, ranging from fast changes in cellular stoichiometry (Twining et al., 2010) to impacts on growth rates. Experimental evidence shows that enhanced inputs of metal micronutrients can either enhance (e.g., Fe, Coale et al., 1996) or inhibit (e.g., excessive Cu, Mann et al., 2002; Jordi et al., 2012) phytoplankton productivity on time scales of hours to weeks. In some coastal settings, metal availability and intracellular concentrations of domoic acid, a neurotoxin, appear to be tightly coupled (Maldonado et al., 2002), indicating an important role for metals in influencing the toxicity and occurrence of harmful algal blooms and the management response needed to mitigate impacts on local communities.

The short time-scale dynamics of micronutrient cycling are incompatible with discrete sampling approaches and require rapid and adaptive *in situ* observations to characterize episodic events and assess the biological implications of changing metal distributions. Developing the ability to obtain continuous, long-term *in situ* time-series for micronutrient metals is thus a pressing need in the field of trace metal biogeochemistry and such a development will improve model parameterizations of the key processes governing the distributions of micronutrients. Such work would better constrain metal fluxes and residence times, and improve our understanding of marine ecosystem dynamics following episodic events, as well as providing a baseline for detecting and predicting climate-driven changes. However, there are, at present, no micronutrient analyzers/sensors with analytical sensitivities suitable for open-ocean determinations of any of the micronutrient trace elements.

There are several regions in the ocean and specific episodic processes that would greatly benefit from high-resolution *in situ* metal measurements. Some of the areas that would provide the

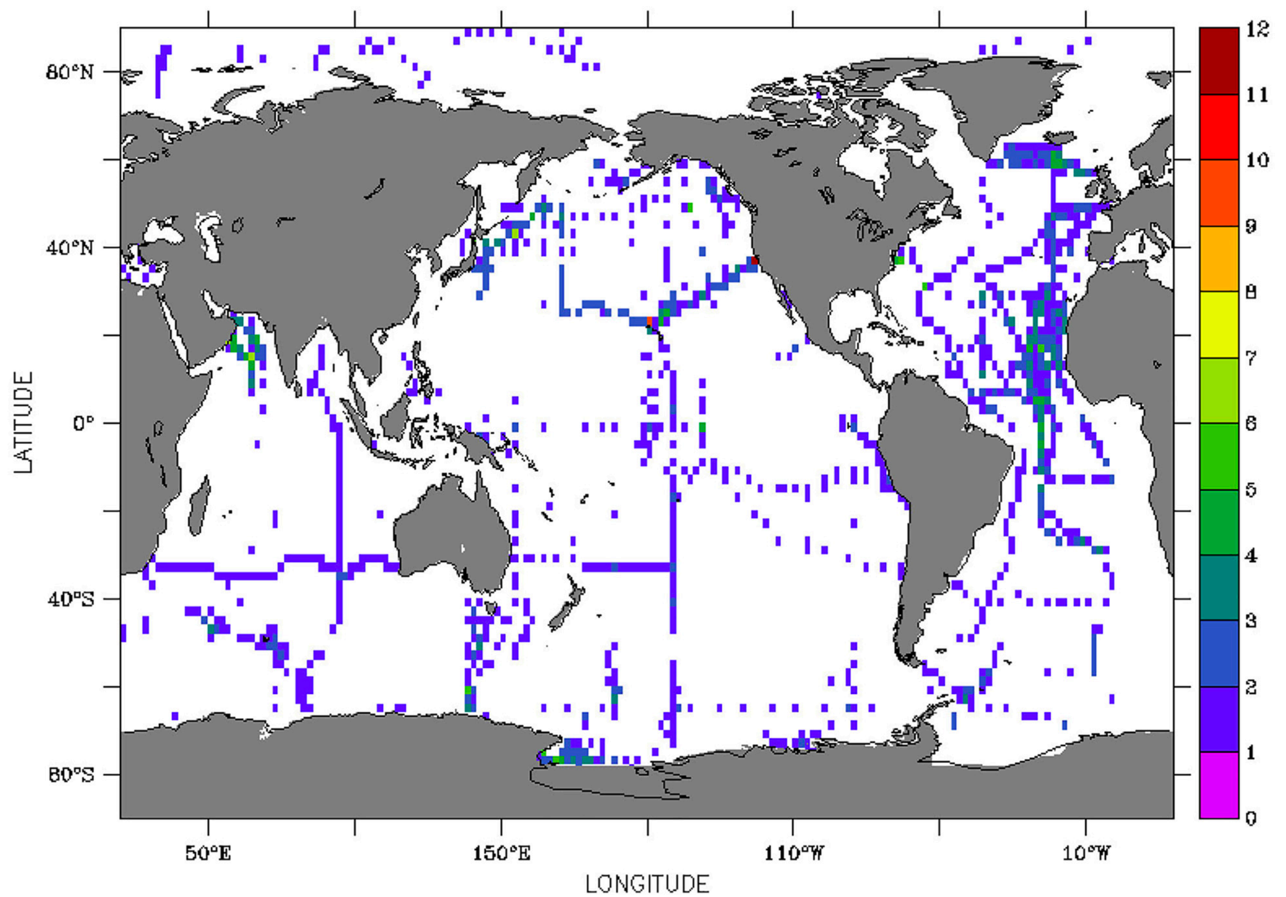

FIGURE 1 | Published dissolved Fe observations as of 2018. To highlight the limited temporal resolution of current Fe observations, the color bar shows the number of unique months of sampling for dissolved Fe within a 2 × 2 degree box in the upper 100 m (*n* = 24,058 observations, datespan: 1978–2014, including all GEOTRACES IDP2017 measurements. The datespan refers to sample collection time and not publication of results). Except for a few repeat observations (e.g., Monterey Bay, HOTS, Arabian Sea, Ross Sea, Indian and Australian Sectors of the Southern Ocean, and North Atlantic), the majority of dissolved Fe observations consist of a one time "snapshot" (i.e., one unique month of sampling).

greatest benefit are either logistically difficult to reach during key seasonal transitions or need high-frequency observations to properly characterize sources and sinks of trace metals. The Southern Ocean, for example, where Fe plays a critical role in modulating productivity, lacks observations during key seasonal transitions (Tagliabue et al., 2012), which would provide important insights into the replenishment and depletion dynamics of Fe during the autumn–winter and winter–spring periods. Additionally, the Southern Ocean experiences variations in frontal positions and mixed-layer depths, affecting the recycling of micronutrients, leading to changes in plankton community structures (Deppeler and Davidson, 2017). An understanding of bioactive micronutrient dynamics would similarly be important in the subarctic North Pacific and Atlantic Oceans, which feature seasonal Fe limitation (Nishioka et al., 2007; Nielsdóttir et al., 2009; Ryan-Keogh et al., 2013; Westberry et al., 2016). Even the Arctic and Antarctic coasts represent important focus areas, where climate scenarios project enhanced continental runoff, and glacial and sea ice melting, which are expected to affect the distribution of metal micronutrients and ligands and thereby impact primary productivity (Deppeler and Davidson, 2017; Rijkenberg et al., 2018). *In situ* ocean metal micronutrient observations at high latitudes during seasonal transitions would greatly improve our ability to monitor and predict the biological responses (across phytoplankton, bacteria, and archaea) to changes in micronutrient concentrations under a changing climate.

The overarching goal of this paper is to make the case for the development and implementation of new *in situ* technologies for marine micronutrient analyses in the decade following OceanObs'19. In addition to core biogeochemical variables (e.g., T, S, O_2, nitrate, Chl-a), we suggest that an ideal autonomous observing system for trace metal micronutrients would include the capability to measure total dissolved concentrations of Fe, Co, Cu, Mn, and Zn with detection limits suitable for open-ocean determinations and field endurance spanning from a month to 1 year depending on the deployment environment (**Table 1**). Following rigorous intercalibration and laboratory testing, we envisage that such a system could be deployed within the decade following OceanObs'19 at fixed observatories

TABLE 1 | Ideal specifications of an autonomous observing system for metal micronutrients in the decade following OceanObs'19.

Element	Open-ocean concentration range[1] (nmol kg^{-1})	Desirable detection limit[2] (nmol kg^{-1})	Accuracy/precision (%)	Endurance	Frequency
Fe	0.03–3	0.1	<10	Month–year	Hourly–biweekly
Cu	0.4–5	0.5	<10	Month–year	Hourly–biweekly
Co	0.003–0.3	0.05	<10	Month–year	Hourly–biweekly
Mn	0.08–5	0.1	<10	Month–year	Hourly–biweekly
Zn	0.05–10	0.1	<10	Month–year	Hourly–biweekly
Ni	2–12	2	<10	Month–year	Hourly–biweekly
Cd	0.001–1.05	0.05	<10	Month–year	Hourly–biweekly

The listed concentration and detection limits refer to total dissolved concentrations. [1]From Bruland et al. (2014). [2]Target detection limits refer to the minimum sensitivity that would be required to detect seasonal concentration changes in the euphotic zone.

and aboard autonomous surface sampling vehicles with a high payload. In the following, we seek to (1) describe the current state of the art and analytical challenges associated with micronutrient analysis; (2) highlight technologies amenable to *in situ* deployment within the next decade, with a particular focus on techniques with potential for sub-nanomolar determinations of metals, including speciation; (3) identify key oceanic regions and processes where *in situ* monitoring would benefit pressing questions in trace metal biogeochemistry; and (4) develop a tangible roadmap for micronutrient metals sensing in the decade following OceanObs'19.

CURRENT ANALYTICAL STATE OF THE ART: SHIPBOARD AND *IN SITU*

Metal micronutrient analysis on discrete seawater samples is typically carried out using inductively coupled mass spectrometry (ICP-MS), Flow Injection Analysis (FIA), and anodic or adsorptive cathodic stripping voltammetry (ASV and AdCSV, respectively). These techniques feature detection limits suitable for open-ocean determinations at sub-nanomolar levels, but are not amenable to *in situ* deployment in their current state (**Table 2**).

ICP-MS

Inductively coupled mass spectrometry is generally regarded as the gold standard for metal micronutrient analysis in shore-based laboratories by virtue of the high precision and low detection limits (picomolar range) afforded by the technique, as well as convenience, since multi-elemental determinations can be performed on a single sample following preconcentration and matrix elimination (Milne et al., 2010; Biller and Bruland, 2012; Lagerström et al., 2013; Minami et al., 2015; Rapp et al., 2017). However, current MS instrumentation requires complex sample pre-treatment, and is too resource demanding (gases, high-vacuum) or not sensitive enough (current miniature platforms) for *in situ* deployment in the foreseeable future.

FIA

Flow Injection Analysis manifolds couple preconcentration/matrix elimination with absorbance, fluorescence, or chemiluminescence detection of individual elements (Fe, Cu, Co, Mn, and Zn, **Table 2**), and have been very popular methods for metal micronutrient analysis onboard ships since the early 1990s (Elrod et al., 1991; Resing and Mottl, 1992; Obata et al., 1993; Nowicki et al., 1994; Measures et al., 1995; Bowie et al., 1998; Laës et al., 2007; Shelley et al., 2010; Klunder et al., 2011; Nishioka et al., 2011; Grand et al., 2015b; Rijkenberg et al., 2018). FIA systems are compact, portable, assembled using commercially available low-cost components, offer low detection limits (<0.1 nM), a rapid analytical throughput and can be connected to continuous underway sampling systems for near-real time surface mapping applications (e.g., Vink et al., 2000; Bowie et al., 2002). However, shipboard FIA systems are prone to drift (Floor et al., 2015), are characterized with high maintenance requirements, and consume large amounts of reagents and power, making them unsuitable for long and/or autonomous deployments (e.g., Johnson et al., 1986). *In situ* chemical analyzers based on flow techniques have been developed for Fe and Mn (e.g., Massoth, 1991; Chin et al., 1992; Okamura et al., 2001; Sarradin et al., 2005; Vuillemin et al., 2009) and Cu (Holm et al., 2008), but the reported limits of detection of these submersible analyzers (**Table 3**), which were originally designed for monitoring metal dynamics in the vicinity of hydrothermal vent systems or in coastal regions, are inadequate for open-ocean determinations.

Voltammetry

Among electrochemical methods, AdCSV with Hanging Mercury Drop Electrode has been widely applied for metal micronutrient analyses onboard ships (Fe, Cu, Zn, and Co, e.g., Achterberg and Braungardt, 1999). AdCSV systems are compact, portable, and commercially available, offering detection limits low enough to determine subnanomolar metal micronutrients (**Table 2**). Flow systems have also been combined to AdCSV for onboard trace metal analysis (Cu, Ni, Zn, Achterberg and van den Berg, 1994, 1996; Co, Daniel et al., 1997). Moreover, AdCSV systems are applicable for speciation measurements by using competitive ligand equilibrium method (Achterberg and Braungardt, 1999). However, AdCSV systems are less accurate than ICP-MS, less stable than FIA systems, need UV digestion for total metal measurements, consume Hg, and often require a stable mercury drop, all of which limit their application for autonomous deployments.

TABLE 2 | State of the art figures of merit for lab and shipboard measurements on discrete samples.

Method	Metal micronutrient	LOD (nM)	Species	Pros and cons
HR ICP-MS[1]	Fe	0.02	Total dissolved	High precision, low detection limits, multi-elemental determinations. Not deployable.
	Cu	0.007	Total dissolved (UV irradiation)	
	Co	0.002	Total dissolved (UV irradiation)	
	Mn	0.007	Total dissolved	
	Zn	0.005	Total dissolved	
	Ni	0.026	Total dissolved	
	Cd	0.0006	Total dissolved	
Shipboard FIA[2]	Fe	0.03	Total dissolved, Fe(II), Fe(III)	Portable, low detection limits, easily assembled using commercially available components. High reagent consumption and maintenance requirements.
	Cu	0.03	Total dissolved, labile Cu(II)	
	Co	0.005	Total dissolved (UV irradiation)	
	Mn	0.03	Total dissolved	
	Zn	0.06	Total dissolved	
	Ni	–	No shipboard FIA method available	
	Cd	–	No shipboard FIA method available	
AdCSV/ASV (Mn and Cd)[3]	Fe	0.1	Total dissolved (UV irradiation)	Portable, low cost, low detection limits. Low reagent consumption, power and maintenance requirements.
	Cu	0.1	Total dissolved (UV irradiation)	
	Co	0.003	Total dissolved (UV irradiation)	
	Mn	0.2	Total dissolved (UV irradiation)	
	Zn	0.07	Total dissolved (UV irradiation)	
	Ni	0.1	Total dissolved (UV irradiation)	
	Cd	0.005	Total dissolved (UV irradiation)	

[1]From Milne et al. (2010). [2]LODs refer to typical detection limits that can be achieved using FIA, not individual analyst reports for each element. [3]From Achterberg and Braungardt (1999).

TABLE 3 | Figures of merit of currently available *in situ* sensors, analyzers, and autonomous samplers for dissolved metal micronutrients.

Species	Method	LOD (nM)	Endurance	Measurement frequency	Reference
Fe(II)	LOC	27	CTD casts	<1 h	Milani et al., 2015
Fe(II) + Fe(III)	LOC	1.9	At least 9 days	45 min	Geißler et al., 2017
Fe(II) + Fe(III)	Miniaturized flow analyzer SCANNER	25	CTD casts	Not listed	Chin et al., 1994
Fe(II) + Fe(III)	Miniaturized flow analyzer ALCHIMIST	70	Not listed	22 h^{-1}	Sarradin et al., 2005
Fe(II) + Fe(III)	Miniaturized flow analyzer CHEMINI	300	Six months	Daily	Vuillemin et al., 2009 Laës-Huon et al., 2016
Total dissolved Cu(II)	Miniaturized flow analyzer	0.8	25 days	Hourly	Holm et al., 2008
Mn	LOC	28	Not reported	<1 h	Milani et al., 2015
Mn	Miniaturized flow analyzer SCANNER	22	CTD casts	Not listed	Chin et al., 1994
Mn	Miniaturized flow analyzer GAMOS	0.23	CTD casts	Not listed	Okamura et al., 2001
Mn	Fiber optics spectrometer ZAPS	0.1	CTD casts	Not listed	Klinkhammer, 1994
Dynamic Cu, Cd, Pb, Zn	ASV	15–30 pM for Pb, 30–50 pM for Cd, 0.5–1.4 nM for Cu	At least 5 days	3 h^{-1}	Braungardt et al., 2009
Fe(II), Mn(II)	Voltammetry	5000 nM Mn(II); 10,000 nM Fe(II)	At least 3 weeks	Four electrodes every 15 min	Luther et al., 2008
Fe, Cu, Co, Mn, Ni, Cd[1]	MITESS (automated trace metal sampler)	HR-ICPMS[2]	6 months		Bell et al., 2002
Fe, Cu, Co, Mn, Ni, Cd[1]	PRISM (automated trace metal sampler)	HR-ICPMS[2]	6 months		Mueller et al., 2018

[1]Automated trace metal clean samplers collect samples that are analyzed upon retrieval of the sampler in shore-based laboratories. Hence, all bioactive elements can be analyzed back in the lab. [2]LODs refer to the actual analytical method being used (here assumed to be HR-ICPMS).

In situ trace level methods (Braungardt et al., 2009; Chapman et al., 2012) have used voltammetry systems that work in surface waters (∼upper 100 m) with anodic stripping voltammetry techniques, with and without gels, on the Hg film electrode surface (**Table 3**). New developments using gel integrated electrodes in *in situ* voltammetric sensors will allow discrimination between labile trace element concentrations from the total dissolved fraction, and thereby provide an indication of metal bioavailability. Initial work was conducted more than a decade ago (Tercier-Waeber et al., 2008), but further work is required. ASV can detect pM levels of trace metals (Zn^{2+}, Cu^{2+}, Cd^{2+}, and Pb^{2+}) by applying a deposition potential for up to 30 min, at a more negative than the reduction potential of the free metal (M) ion, $[M(H_2O)_6]^{n+}$ to form M(Hg). To determine total metal concentrations, metal–ligand (M–L) complexes need to be dissociated so that the metal can be detected. There are two ways to do this and only the second has been used for *in situ* work: (1) acidification of the sample to pH ∼2 followed by UV oxidation prior to sample analysis and (2) application of a sufficiently negative potential to break down the complex at the electrode by reduction to M(Hg) plus L. Two reports (Braungardt et al., 2009; Chapman et al., 2012) have used an applied potential of −1.2 V vs. a Ag/AgCl reference electrode to determine the potentially bioavailable metal, which is operationally defined as the free ion plus labile M–L complexes. Conditioning or electrochemical cleaning of the electrode is accomplished between measurements to give excellent precision and an electrode lifetime of up to 2 weeks. Unfortunately, some unknown M–L complexes (e.g., Croot et al., 1999; Rozan et al., 2003) cannot be completely destroyed at −1.2 V, as the thermodynamic stability complexes are so strong that a more negative deposition potential (∼−1.6 V) must be applied to break up the M–L complex.

For Fe(III), competitive ligand exchange cathodic stripping voltammetry techniques (CLE-CSV) are required to detect pM levels of Fe. No *in situ* method has been developed and tested (Lin et al., 2018), and unknown Fe–L complexes will need to be broken up by acidification and UV oxidation, then buffered to circumneutral pH, so the competitive ligand can complex the Fe(III) for analysis.

IN SITU MICRONUTRIENT OBSERVATIONS: CHALLENGES

Choice of Infrastructure

Independent of the target parameters, *in situ* monitoring in remote oceanic settings typically requires instrumentation that is robust, compact, fully automated, and capable of operating without servicing for extended periods of time with minimal reagent needs, low power consumption, and high data storage capacity (Delory and Pearlman, 2018). In several areas and seasons, such as the wintertime Southern Ocean, infrastructure and attached devices must be able to withstand extreme weather conditions. The power requirements of prototype sensor systems, which will depend on the analytical measurement frequency and environmental conditions (temperature, pressure), will need to be carefully evaluated in order to determine on which platform or vehicle the sensor package can be deployed. Platform-based observatories can support large and power-hungry instruments, while mobile gliders and profilers will require miniaturized, light-weight sensors with low power consumption and high measurement frequencies. The following sections provide more details on some of the challenges that *in situ* sampling and observation methods for trace micronutrients will face.

Analytical Sensitivity and Field Endurance

In the open ocean, most micronutrient metals are present at sub-nanomolar concentrations in surface waters that increase to a few nanomolar in deeper waters (Bruland et al., 2014). Monitoring subtle variations in bioactive micronutrients in the open ocean thus requires the development of highly sensitive analyzers characterized with detection limits <0.1 nM and a precision on the order of ±0.05 nM (**Table 1**). In addition, micronutrient analyzer prototypes should have an endurance of at least 1 month, irrespective of the measurement frequency, to enable preliminary deployments at ocean observatories serviced at monthly intervals. However, in remote settings such as in the Southern Ocean where servicing can only be performed once yearly, a 12-month endurance would be necessary with a measurement frequency suitable to constrain seasonal changes (i.e., twice daily). While some automated *in situ* chemical analyzers provided month-long records of Fe (Chapin et al., 2002; Laës-Huon et al., 2016), Mn (Klinkhammer, 1994; Okamura et al., 2001), and Cu (Holm et al., 2008) in coastal settings and in the vicinity of hydrothermal vents (**Figure 2**), there are currently no autonomous analytical techniques that can measure micronutrient metal species at the necessary detection limits for open ocean work.

Among the various analytical techniques for metal micronutrients amenable to *in situ* deployment (electrochemistry, wet chemistry), miniaturized flow-based techniques coupling analyte preconcentration with optical detection (spectrophotometric, fluorometric, or chemiluminescent) have the greatest potential to achieve the analytical sensitivity and accuracy necessary for autonomous open-ocean micronutrient determinations within the next decade. However, the use of reagents may ultimately limit the endurance of wet chemical analyzers for long-term monitoring applications (>1 month) owing to reagent storage and shelf life. In addition, sub-nanomolar detection of micronutrients using wet chemical analysis is often based on spectrophotometric catalytic reaction methods, which require precise thermoregulation of the instrument (reaction chamber, reagents, and *in situ* standards) (Laës et al., 2005). Temperature regulation is a technical challenge (mechanical composition of the housing, power consumption, electronic enslavement, temperature inertia, and the use of multivariate standard curves) that depends on the range of temperature variation encountered in the environmental setting: surface buoys, profilers, or deep seabed observatories. These limitations suggest that the development of novel analytical chemistries

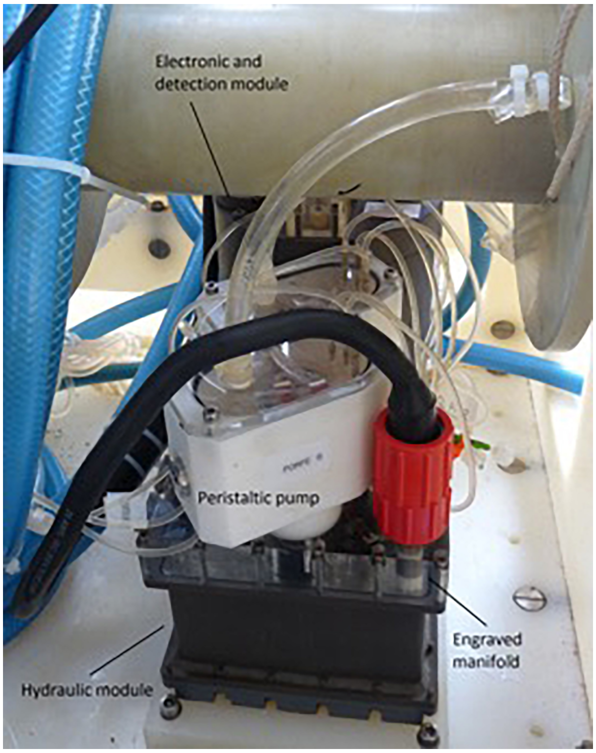

FIGURE 2 | The CHEmical MINIaturized analyzer (CHEMINI) for iron determinations in the vicinity of hydrothermal vents implemented on the EMSO-Azores MoMAR observatory infrastructure at 1700 m depth, hydraulic module: 240 * 150 mm, electronic module: 140 * 264 mm (Laës-Huon et al., 2016).

that are not responsive to temperature variations would be highly desirable.

Avoiding Contamination

Contamination is one of the major hurdles associated with trace metal analysis, and will require careful consideration in the design of autonomous analyzers housings (e.g., using metal free components such as Teflon or LDPE that are in contact with the sample), as well as the selection of non-contaminating platforms from which to deploy them. The extremely low natural concentrations of metals and their ubiquity in traditional sampling equipment (ships, frames, bottles) have led trace metal geochemists to develop extreme methodologies to avoid contamination during all phases of sampling and analysis. Specialized sampling systems for vertical profiling have been developed using polymer-based hydrowires and plastic-coated or titanium rosette frames fitted with sampling bottles that are lined with Teflon or constructed using high-purity plastics (de Baar et al., 2007; Measures et al., 2008; Cutter and Bruland, 2012). To avoid introduction of contaminants following recovery of the sampling package, subsampling is carried out in class 100 filtered air spaces and rigorously cleaned plastic containers are used for sample storage. *In situ* monitoring will obviously eliminate some of these issues, most notably during sample acquisition and processing (filtration, acidification) and by removing the need to transfer and store the sample into a clean container prior to analysis. However, not all available deployment platforms will be suitable for *in situ* metal sensors. For example, deploying a sensor on a moored profiler will require the use of non-metallic components or the addition of vanes to orient the sensor intake upstream of the mooring line. Therefore, some existing ocean observing infrastructure (OOI) will need to be customized in order to accommodate new micronutrient sensors while other ocean observing assets may not be suitable at all.

Biofouling in oceanic environments can take place very quickly, particularly in surface waters during periods of high biological productivity, and can lead to data quality deterioration in less than a few weeks' time (Delory and Pearlman, 2018). Processes to minimize biofouling effects are therefore necessary to ensure the long-term reliability of *in situ* monitoring devices. Considering that the most effective biofouling prevention relies on the use of metals (e.g., Cu coatings), the development of metal-free biofouling coatings may be necessary to prevent contamination of metal sensors/analyzers, particularly in regions where sub-nanomolar metal concentrations are prevalent. The intricacies of trace metal analysis will thus potentially restrict the integration of newly developed metal sensors into existing ocean observing assets.

Metal Speciation

Metal micronutrients can exist in a variety of redox states, chemical species, and in a range of operationally defined physical forms. The majority of historical metal micronutrient observations consists of total dissolved concentrations, which are obtained following separation from the particulate phase using 0.2–0.45 μm pore size filters and acidification to pH < 2 using a strong acid. The total dissolved metal fraction includes colloids, organic and inorganic complexes, as well as free hydrated ions ($<$0.02 μm), which may be the most bioavailable species to biota. The operationally defined total dissolved metal fraction has been adopted based on historic sample filter sizes. Acidification allows sample integrity to be preserved prior to analysis and for the comparison of data from one location to the other and among various analytical labs. It also allows organically complexed metals to be dissociated and thus make them accessible to the analytical methodology.

To provide continuity with historical data, it is desirable to develop *in situ* metal micronutrient sensors with the capacity to measure total dissolved metal concentrations. However, this will also pose a technical challenge for long-term unattended observations, as it implies samples which need to be filtered and acidified for longer than a few minutes prior to analysis. The filters would need to be either automatically changed or cleaned at regular intervals to provide a representative sample of the total dissolved metal concentrations and to avoid clogging of the overall system. Additionally, while obtaining bulk total dissolved concentrations is geochemically meaningful in order to quantify external fluxes and budgets of micronutrient metals (e.g., for Al and Fe for dust deposition), its interpretation is challenging when attempting to determine which metal species are most available to resident biota. In this regard, the development of *in situ* metal analyzers that do not require pre-treatment (filtration and acidification) may provide additional insights into the reactivity of metal micronutrients in their natural state, thereby providing measurements that are more representative of bioavailability than total dissolved concentrations. It would also simplify *in situ* chemical analyzer manifolds and increase their measurement frequency, by removing one analytical step characterized with slow kinetics (i.e., the liberation of metals from ligand complexes). However, if filtration is avoided, particulates and biofouling could limit long-term deployment by blocking channels of microfluidics systems. Further assessment is required to fully resolve this issue.

Long-Term Accuracy: *In Situ* Calibration

To maintain analytical accuracy over long (months) periods, micronutrient metal sensors will need to be calibrated autonomously and accuracy assessed through the use of external standards. In the case of sensors measuring total dissolved metal concentrations (i.e., filtered and acidified), *in situ* calibration can be performed using acidified onboard standard(s) run at regular intervals throughout the deployment period. The shelf life of acidified onboard standards for total metal determinations is not expected to be an issue, as illustrated by the long-term stability of the SAFe and GEOTRACES community standards, which have exhibited stable concentrations for a variety of metals over several years. Quality control will prove more challenging for *in situ* speciation determinations, since it will be more difficult to preserve the standard solution (e.g., Fe (II)) over extended deployment times.

Measurement Frequency, Data Acquisition

End-users desire sensors that can be deployed for a minimum of 1 month and up to 12 months with confidence, have high measurement frequencies (hours to days; **Table 1**) and minimal servicing requirements. Ideally, these sensors would employ real-time satellite reporting of the metal micronutrient concentrations along with other ancillary biogeochemical parameters (e.g., T, S, Chl-a) to enable adaptive sampling. Increasing the measurement frequency, which depends on the environment, sampling mode and research questions, implies an increase in data storage capacities. For current metal micronutrient analysis onboard ships, post-cruise data processing (reagent blank, optical blank, electrochemical background subtraction) is carefully employed. Such high-quality corrections will need to be implemented for the next generation of *in situ* sensors and one of the next challenges would be to consider when and how to apply corrections from *in situ* calibration or from *in situ* quality control. Globally accepted definitions of the speciation (physical, redox, chemical speciation) for metal micronutrients concentrations produced by sensors will also need to be considered before integrating them into databases and global models.

Fostering Widespread Use

The commercialization of plug-and-play micronutrient metal sensors with sub-nanomolar sensitivity is unlikely within the next decade due to the relatively small market for such devices and the high costs associated with prototype development, validation, and manufacturing of the final product. For this reason, most micronutrient metal sensor development work will continue to be carried out at research institutions, where prototypes are engineered in house using specialized instrumentation with a high level of expertise for fabrication, operation, deployment, and data processing (e.g., Klinkhammer, 1994; Okamura et al., 2001; Holm et al., 2008; Laës-Huon et al., 2016). In addition, the development work required to convert early prototypes into robust, reliable, and validated instruments for month-long deployments in the open ocean spans across more than one typical 3–5 year funding cycle. It is also difficult to sustain using research funding schemes that often prioritize innovation over continued development and validation. Thus, emerging sensors rarely go beyond the prototype stage, which hinders extensive use by the wider community.

To foster widespread deployments, one possibility would be to promote the development of autonomous micronutrient analyzers assembled using commercially available or 3D printed components and operated using open-source electronics, microcontrollers, software, and instrument housings. This strategy, which proved popular with the Do It Yourself (DIY) environmental-sensor makers community, may facilitate the fabrication and operation of low cost wet-chemical micronutrient metal sensors and maximize replication and operation by a greater number of end users worldwide. Indeed, the current popularity of custom-made FIA manifolds for the analysis of trace micronutrients onboard ships may be attributed to the fact that these manifolds can be built using commercially available components that do not require a high degree of expertise for assembly and software control. Applying a DIY open-source strategy and readily available technology would greatly simplify the developmental pathway from laboratory to the ocean and would lower the overall costs of the development and production of wet chemical analyzers. This approach will likely attract more analytically inclined trace metal geochemists to participate in the development. Consequently, the community would greatly increase the number and capability of prototype analyzers for bioactive micronutrient metals that could be readily deployed and tested on short-term missions aboard autonomous surface vehicles or at coastal monitoring nodes. Such an increase in the number of sensors will ultimately lead to robust concentration reports of defined sets of intercalibrated metal species, determined with well-accepted sampling and analytical protocols.

TECHNOLOGIES WITH POTENTIAL WITHIN A DECADE

Several analytical technologies have the potential to be deployed *in situ* for micronutrient metal analysis in the decade following OceanObs'19 (**Table 4**). These include (1) miniaturized wet chemical analyzers, which will likely achieve the analytical sensitivity required for open-ocean determinations but will have a limited endurance due to power requirements, as well as

TABLE 4 | Summary of attributes of potential techniques for *in situ* metal micronutrient determinations within the next decade.

Technique	Advantages	Disadvantages
Wet Chemical Analyzers	High resolution, accuracy, and precision Relatively fast response time Can be calibrated *in situ*	Expensive Many analyzers have high power requirements Relatively bulky Biofouling High maintenance costs Longevity limited by reagent use and stability Waste generation
Electrochemical methods	Inexpensive Easy to use Large measurement range Speciation measurements Not influenced by turbidity	Lower resolution, accuracy, precision Subject to ionic interferences, organic matter High instrument drift Biofouling Difficult to calibrate *in situ*
Autonomous trace metal clean samplers	Good starting point for remote locations with challenging environmental conditions (i.e., high latitudes) Multi-elemental determinations	Limited measurement frequency More prone to storage and contamination artifacts Require expert shore-based analysis Biofouling
Passive preconcentration samplers	Inexpensive Easy to use No power source Preconcentration included Multi-elemental determinations	Lower resolution, accuracy, precision Require lab testing and intercalibration Integrative concentration measurement which is hard to calibrate Require expert shore-based analysis

reagent stability and consumption, and (2) voltammetric sensors which are proven in high metal concentration environments (e.g., coastal systems, continental margins, and hydrothermal vent fields), and (3) passive preconcentration samplers, which have the potential to be mass deployed at low cost but will need to be recovered periodically for analysis, and thus will be most amenable to deployment in easily accessible coastal regions, where they could be incorporated in citizen monitoring programs.

Miniaturized Wet Chemical Analyzers

Lab-on-Chip

The miniaturization of existing reagent-based assays holds great promise for micronutrient sensing on moorings, cabled-arrays, and autonomous underwater vehicles (Statham et al., 2003, 2005; Gamo et al., 2007; Doi et al., 2008). Recent advances in microfabrication have led to the development of automated Lab-on-Chip microfluidic analyzers, which are compact, self-calibrating, fully automated, low cost, and operate standard absorbance methods with low power and reagent consumption (**Figure 3**). These instruments have been deployed for up to 2 months in estuarine and coastal settings, providing hourly macronutrient data (N, P) with an accuracy comparable to that of laboratory-based auto-analyzers (Beaton et al., 2012; Clinton-Bailey et al., 2017; Grand et al., 2017; Vincent et al., 2018). While fully automated Lab-on-Chip analyzers were recently developed for Fe (II) and Mn, their detection limits [2 nM, Fe(II), Geißler et al., 2017; 28 nM Mn, Milani et al., 2015] restrict their use to areas characterized by high concentrations, such as estuarine and coastal settings, oxygen minimum zones, and hydrothermal plumes. To achieve the sensitivity (~0.1 nM) necessary for metal micronutrient determinations in open ocean settings (**Table 1**), analyte preconcentration protocols compatible with the Lab-on-Chip technology will need to be developed and on-chip detection

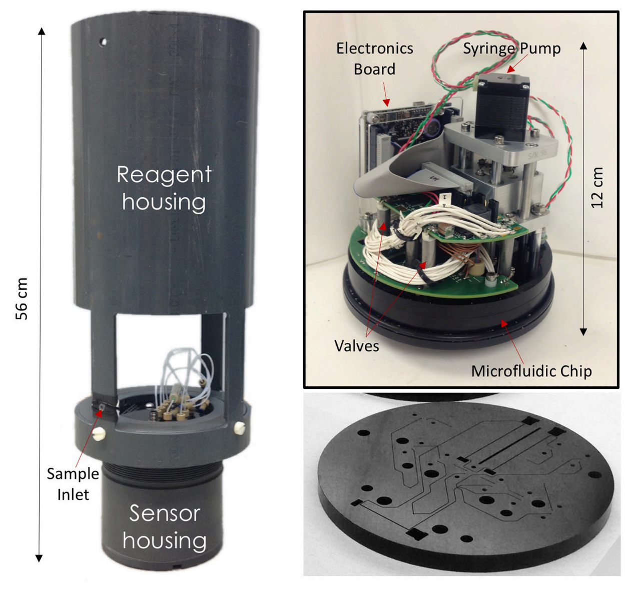

FIGURE 3 | Lab-on-Chip phosphate analyzer. Left: fully assembled sensor with reagent housing. Top right: Analyzer prior to placement in watertight housing. Bottom-right: microfluidic chip showing micromilled fluidic manifold and absorbance flow cells prior to assembly. From Grand et al. (2017).

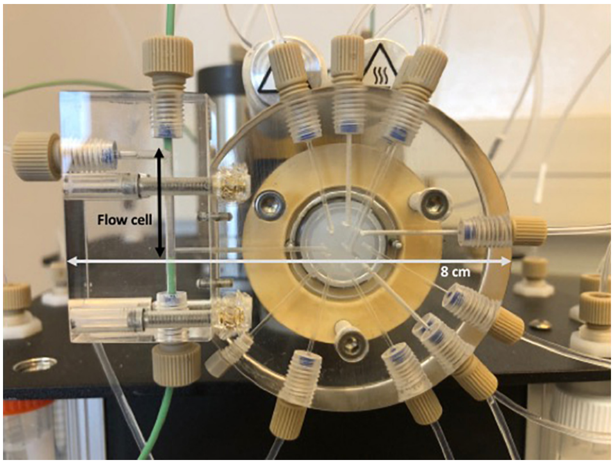

FIGURE 4 | Close-up of the lab-on-valve (LOV) module of a typical micro-Sequential Injection analyzer configured here for absorbance detection. The LOV can be configured for absorbance, fluorescence, or chemiluminescence detection by repositioning the optical fibers (green tubing) around the flow cell and using appropriate detectors (e.g., miniature spectrophotometer, photomultiplier tube). The LOV ports are used to aspirate and mix microliter volumes of reagents and sample, which are then propelled to the flow cell for analyte quantification (rectangular block, left-hand side).

capabilities extended to fluorescence, chemiluminescence, and/or Cavity Ringdown Spectroscopy. These ongoing developments will enable Lab-on-Chip sensors to operate existing wet chemical assays for Mn, Fe, Zn, Cu, and Co within the next decade.

Micro-Sequential Injection Lab-on-Valve

Micro-Sequential Injection analyzers are another class of automated, miniaturized wet chemical analyzers with potential for *in situ* deployment (**Figure 4**). Presently best suited to laboratory and shipboard determinations (Oliveira et al., 2015; Grand et al., 2016), these compact instruments share many of the features that have made FIA systems popular for shipboard metal micronutrient determinations. Indeed, Micro-Sequential Injection analyzers are made using commercially available components, are easily customizable, fully automated, and can operate absorbance, fluorescence, and chemiluminescence determinations coupled with analyte preconcentration to reach detection limits in the sub-nanomolar range. However, unlike FIA systems, they are characterized with low reagent consumption (100s of microliters per sample), are less prone to drift, and do not require much maintenance, which make micro-Sequential Injection analyzers better suited to long-term unattended operation relative to their FIA counterparts.

At present, the application of micro-Sequential Injection to micronutrient metal determinations at open ocean levels is limited to the shipboard analysis of total dissolved Zn and Fe, with reported detection limits of 50 pM for Zn (Grand et al., 2016) and 1 nM for Fe (II) (Oliveira et al., 2015). Micro-Sequential Injection is thus a proven analytical technology for sub-nanomolar metal micronutrient detection, but unlike Lab-on-Chip platforms, micro-Sequential analyzers have not yet been engineered for *in situ* deployment. Further work is required to integrate all micro-Sequential Injection components (Lab-on-Valve, pump, detectors, electronics, and microcontroller) into compact, submersible housings, which will enable the deployment of micro-Sequential Injection analyzers at fixed locations (cabled observatories) and possibly for surface mapping applications onboard unmanned surface vehicles (e.g., wave gliders, Sail Drones, Autonomous Underwater Vehicles) in the decade following OceanObs'19.

Electrochemical Methods

One possibility for *in situ* applications of ASV is to use a solid working electrode instead of a mercury drop (Sundby et al., 2005; Luther et al., 2008). A new *in situ* copper microsensor using a vibrating gold microwire working electrode (Gibbon-Walsh et al., 2012), an iridium wire counter electrode, and a solid state reference electrode made of AgCl coated with an immobilized electrolyte and protected with Nafion has recently been developed. This sensor is able to detect Cu at nanomolar concentrations in coastal waters (2.0 ± 0.5 nM) and performs speciation measurements. The current version of the system has been deployed *in situ* for hydraulic, electronic, and pressure tests (2750 m) aboard the *Nautile* submarine (Cathalot et al., 2017). Although the detection limit is currently too high for open-ocean applications, it may be lowered by increasing the deposition step time, thereby offering another prospect for *in situ* ASV determination of Cu at sub-nanomolar levels. Conditioning and electrochemical cleaning of the electrode remains, however, as for the classical *in situ* voltammetric systems, a considerable challenge.

For environmental systems such as hydrothermal vents, diffuse flow ridge flanks, seeps, and sediments that are metal sources with higher concentrations (micromolar) of Fe and Mn, *in situ* solid Au/Hg working electrodes, have been tested and calibrated to 5000 m and from 2 to 60°C (Luther et al., 2008; Cowen et al., 2012). These voltammetry systems have been operated using the *Alvin* submersible and the *Jason II* ROV in dynamic flowing vent and diffuse flow waters. In such environments, autonomous systems have been deployed for up to 3 weeks. These systems are amenable to integration into Ocean Observing Initiative assets where power is not limited. Fast scan voltammetry techniques (∼2 s for complete data acquisition) were used without a stripping or preconcentration step due to the elevated metal concentrations in these environments. The method uses a 5 s conditioning or cleaning step so that multiple analytes can be detected simultaneously every 7–10 s to study the dynamics of the source waters in these environmental systems.

In Situ Collection, Preservation, and Preconcentration

Serial Automated Trace Metal Clean Samplers

During the development and testing phase of the chemical analyzers and sensors described above, it would be desirable to foster the development and use of trace metal clean devices that can collect and preserve samples for later laboratory analysis. The benefits of this approach are twofold. First, developing the capability to collect and preserve trace metal clean seawater samples *in situ* would allow obtaining time-series in environments that are only accessible once a year and are characterized with challenging conditions for any newly developed sensor, such as in the Southern Ocean. Second, the application of proven, autonomous trace metal clean samplers would be extremely valuable for testing and intercalibration of future *in situ* analyzers and sensors. The technology for autonomous trace metal samplers is already available and mature enough to be deployed within the next decade. Examples include the MITESS sampler (Bell et al., 2002), the newly developed PRISM sampler (Mueller et al., 2018), ANEMONE-11 (Okamura et al., 2013), the commercially available McLane Labs Remote Access Sampler (RAS), and the Biogeochemical AUV sampler CLIO, which is currently under development at WHOI. Each of these different autonomous sampler types has different advantages and disadvantages for remote sampling of low level, trace metal clean open ocean seawater, and the type of application will determine which one(s) are suitable. Some further refinements may be necessary to optimize the sampler type for the project needs (e.g., endurance, type of deployment, ocean conditions).

Passive Preconcentration Samplers

A complementary approach to automated samplers and *in situ* analysis of micronutrient metals is the development of passive sampling techniques. Passive sampling is based on the diffusion of the analyte across a porous membrane (hydrophobic or hydrophilic) into a receiver phase (solid or liquid), where the analyte is accumulated at a rate that is proportional to the external concentration. After a set deployment period (days, weeks, months), the sampler is retrieved, and back in the laboratory the analyte is extracted from the receiver phase and analyzed. Passive samplers thus provide a time-averaged weighted concentration of the species of interest, which, in contrast to discrete sampling, increases the likelihood of capturing intermittent sources and sinks. In addition, passive samplers have no moving parts, do not require a power source, are inexpensive, and could thus be mass deployed, particularly in coastal regions where they can be easily retrieved. Another notable feature of passive samplers is that they collect and pre-concentrate the analyte in one step, which is particularly beneficial for metal species present at sub-nanomolar levels in seawater.

There are several types of passive sampling devices that have been developed over the past 30 years. Among these, Diffusive Gradient Thin (DGT) Gels and, more recently, Polymeric Inclusion Membranes (PIMs) have been deployed in coastal and inland waters (Twiss and Moffett, 2002; Shiva et al., 2016; Almeida et al., 2017), and appear to have the most potential for micronutrient metal determinations. DGTs were also used successfully (analyzing a suite of trace metals at sub-nanomolar level) on discrete samples from the Southern Ocean (Baeyens et al., 2011) and more recently aboard a SeaExplorer glider in the Mediterranean Sea (Baeyens et al., 2018). It should be noted that passive samplers collect samples over the time interval of the deployment. Thus, while they are more likely to collect transient signals over the time interval of the deployment, they will also average all transient signals over the time interval of the deployment. Prior to widespread use, these techniques will require further laboratory testing and validation to determine which metals species are being measured (free ions and small and possibly weaker metal–ligand complexes), and to quantify metal concentrations, given poorly constrained diffusion rates.

A ROADMAP TOWARD AUTONOMOUS MICRONUTRIENT OBSERVING SYSTEMS

There are several regions (e.g., high latitudes) and specific episodic processes (e.g., seasonal transitions) that would greatly benefit from high-resolution *in situ* metal measurements in order to characterize and quantify sources and sinks of trace metals in the global ocean. Sensor development would also address an urgent need to improve predictions, in a rapidly changing ocean, of the plankton response (phytoplankton, bacteria, and archaea) to variations in micronutrient concentrations, following episodic events and/or at seasonal transitions.

Of the bioactive metal micronutrients (Fe, Zn, Co, Mn, Co, Ni, and Cd), Fe has received the most attention considering that it limits primary productivity in large parts of the world's ocean, and imparts a significant influence on phytoplankton species composition. As such, Fe should probably be the prime target for sensor development and field implementation in the next decade, not only to improve the quantification of fluxes but also to better constrain the parameterizations of regional and global numerical models (Tagliabue et al., 2016). In addition, the technology and lessons learned from the development of an open ocean Fe sensor could facilitate the development of sensors for other important metal micronutrients, particularly for reagent-based analyzers which will operate using similar fluidic architectures and detection schemes. However, subsequently, high-frequency observations would be desirable for the full suite of essential trace elements, such as zinc (Southern Ocean: Vance et al., 2017; subarctic North Pacific: Kim et al., 2017).

Some of the areas that would provide the greatest benefit (e.g., high latitudes) are logistically difficult to reach. The ability to meet the challenge of producing metal sensors capable of operating in these remote open ocean regions is unlikely in the decade following OceanObs'19 due to the immaturity of metal-sensor development at this time. However, within this timeframe, it is reasonable to expect the development of sensors for less extreme environments at sites that currently host time series activities (HOT, BATS, CALCoffi, etc.), at cabled ocean observatories, which are regularly serviced, or in areas where metal concentrations are above open ocean levels. At remote high latitudes, the development and implementation of autonomous trace metal clean sample collectors and/or passive samplers retrieved at yearly intervals with ensuing shore-based analysis is an achievable outcome within the next decade. In the following, we describe a series of tangible outcomes, that should be the focus of research and development efforts in the decade following OceanObs'19.

Testing and Intercalibration

Development of metal sensors for remote deployment requires analyzers/sensors that are well tested in terms of electronic performance, endurance, and analytical performance under all operating conditions (i.e., freezing conditions and remoteness). Thus, before implementing *in situ* chemical analyzers, electrochemical sensors, and passive samplers on various types of platforms, the systems must be rigorously tested and validated under controlled laboratory conditions. Such long-term unattended laboratory tests should be standardized and include (1) temperature and pressure effects on analytical sensitivity, drift, and reagent shelf life (for methods sensitive to such changes, e.g., Okamura et al., 2001; Weeks and Bruland, 2002); (2) aging of the sensor (sunlight, seawater spray, vibrations); (3) the potential for biofouling and ways to mitigate it without metal-based biocides; and (4) a thorough intercalibration of the analyzer/sensor data quality (including speciation) with that of established techniques with input and guidance from the GEOTRACES community of analysts. These tests, which should at least be performed over a month-long period, will provide a first estimate of required operational settings in terms of robustness, reliability over time (figure of merits, drift), and lifetime without maintenance and power consumption, each of which will depend on the environmental conditions of the deployment and the analytical measurement frequency required for a given application. Such tests are theoretically feasible using existing monitoring platforms, pressure chambers, and test pools. However, as mentioned above, these tests are difficult to sustain beyond the typical 3–5 year time scale of a typical method development research grant and require resources that are not available to all developers (i.e., pressure chambers and test pools). Yet, they are critical to ensure end-users' acceptance and foster widespread usage by the community.

Surface Mapping Along Dry and Wet Atmospheric Deposition Gradients

Areas where dust deposition is important would be well served by the addition of high-frequency measurements. Dust deposition is an important source of trace metals to the open ocean, especially for Fe, whose availability influences productivity at high latitudes and nitrogen fixation rates in oligotrophic subtropical gyres (Tagliabue et al., 2017 and references therein). Regions of known elevated dust deposition (e.g., the subtropical North Atlantic; Sedwick et al., 2005; Buck et al., 2010) would be expected to exhibit large dissolved metal gradients at concentrations significantly above other open ocean locations, thereby facilitating the establishment of new sensor systems. High-resolution autonomous surface mapping in these regions could improve understanding of the variables affecting metal dissolution including rainfall, dry deposition, and the sea surface microlayer, all of which are currently not well understood given the paucity of data at appropriate spatial and temporal resolution (Baker et al., 2016). Such measurements could also allow examination of the residence time of Fe in the surface ocean and the impact of deposition events on biological activity.

Although not a bioactive trace metal micronutrient, aluminium (Al) is considered a good proxy for dust deposition and thus the input of Fe to the surface ocean (Measures and Vink, 2000; Grand et al., 2015a; Anderson et al., 2016). The residence time of Al is considerably longer than that of Fe, but much shorter than that of Mn, suggesting that it reflects Fe inputs on a daily-to-annual time scale. Current benchtop analytical techniques (e.g., Resing and Measures, 1994) are sensitive enough to analyze Al in areas of intense dust deposition without a preconcentration step, making the development of an Al sensor for these areas an interesting proposition. Such a sensor would certainly complement any new Fe sensor and would provide a data set to evaluate changes in Fe inputs. This vision could be achieved within a decade, for example, by deploying Fe and Al analyzers on autonomous surface sampling vehicles, such as Wave Gliders and Sail Drones, for month-long missions. Sail Drones are perhaps most amenable to hosting prototype *in situ* wet chemical analyzers due to their power availability, size, and availability of dry instrument space above the water line (Voosen, 2018).

Time Series

Metal micronutrient time series are rare. They are mainly focused on Fe, of limited temporal resolution and difficult to maintain over the time period needed to decipher seasonal variations, episodic events, and their impact on marine ecosystem dynamics (Boyle et al., 2005; Sedwick et al., 2005; Nishioka et al., 2011; Fitzsimmons et al., 2015; Barrett et al., 2015). Developing the capacity to instrument coastal and open ocean time-series sites, which are well characterized and visited on a regular basis for sampling and servicing (e.g., BATS, HOT, CalCOFI), would be a very desirable outcome in the decade following OceanObs'19. Ocean observing sites that are already instrumented with a mooring would be a good place to start (e.g., Ocean Station Papa, OOI Endurance Array) considering that power-hungry analyzers with relatively large payloads could be deployed and serviced at regular intervals during their development stages.

While the ultimate goal is to develop the capacity to monitor bioactive trace elements *in situ* at sub-nanomolar concentrations in open ocean settings, obtaining long-term datasets in areas that are not as challenging analytically (in terms of detection limits) and logistically (in terms of remoteness) constitutes an obvious first step. In this regard, acquiring time-series records in coastal regions experiencing seasonal upwelling (e.g., Monterey Bay; Elrod et al., 2008) and typically showing enhanced metal concentrations would be logistically ideal locations. Newly developed sensors/analyzers/samplers can be tested and validated (e.g., Geißler et al., 2017), integrated with other biogeochemical sensors (e.g., macronutrients, Imaging FlowCytobot), and be potentially used to investigate how bioactive metal micronutrient availability influences domoic acid production and the onset of harmful algal blooms in coastal regions (Maldonado et al., 2002). In addition, the GEOTRACES community could capitalize on existing micronutrient analyzer prototypes to improve quantification of metal fluxes at interfaces (e.g., **Figure 2**; Laës-Huon et al., 2016). For example, the temporal variability of hydrothermal emissions, plume chemical speciation, and distal transport of Fe could be explored further using a series of analyzers deployed in the wake of a vent system (Waeles et al., 2017). Metal fluxes from reducing sediments and the metal dynamics in oxygen minimum zones characterized by elevated metal concentrations could also be explored. For example, trace metal sensors could be integrated with existing ocean observing assets, such as the long-term time sampling program in Saanich Inlet (BC, Canada), a low-oxygen fjord, with monthly monitoring measurements, and a VENUS cabled observatory (Ocean Networks Canada). The implementation of such systems should be easily accomplished as it has already been performed on one of the deepest parts of the Ocean Networks Canada (Grotto Hydrothermal Vent, Endeavour Field, 2186 m) from 2011 and 2013 to collect iron concentrations (CHEMINI *in situ* analyzer) and to link them to the chemosynthetic environment and its related fauna (Cuvelier et al., 2014, 2017).

CONCLUSION AND RECOMMENDATIONS

Trace metal biogeochemistry is integral to our understanding of marine biogeochemical cycling and ocean productivity. The next decade offers the opportunity to capitalize on the findings of the GEOTRACES program, and the growing Ocean Observatories Initiative (assets, autonomous vehicles) to investigate processes and regions at the spatial and temporal resolution necessary to constrain fluxes, residence times, and biological and chemical responses to varying metal inputs and distributions in a changing ocean. Capitalizing on this opportunity, however, requires the development of sensors capable of measuring trace metal micronutrients at levels found in the open ocean. In the next decade, we can make progress with the development of techniques with increased sensitivity and sensor support infrastructure. In addition, we can deploy existing flow techniques, electrochemical methods, and passive samplers on dry platforms including moorings, Sail Drones, autonomous underwater vehicles, ocean observing assets, and ships of opportunity.

To meet this opportunity, however, significant resources must be invested to accomplish goals on several fronts. The first is the improvement in the analytical sensitivity of existing sensors, chemical analyzers, and their underlying chemistries. Novel chemical assays must be developed for those underlying chemistries that employ stable reagents and that are insensitive to temperature variations. Secondly, we must reduce sensor size and power requirements. In addition to deploying existing techniques, it is essential to develop an open-source "DIY" infrastructure to allow ease of sensor development and a mechanism by which scientists can rapidly adapt commercially available technology to *in situ* applications. Finally, to meet this opportunity, sensor technologies will need to demonstrate the endurance and comparability of *in situ* sensor data with established techniques in controlled lab conditions. Each of these areas will best be served through interdisciplinary collaborations/joint proposals with government, industry, or academic partners. The creation of an international working group of trace metal sensor developers facilitating regular meetings and workshops and involving the engineering, oceanographic, and analytical chemistry communities could accelerate the delivery of new technology that can be applied to *in situ* metal determinations in the decade following OceanObs'19.

It should be noted that no sensor is likely to be appropriate for every application. Thus, at this stage, no particular technology should be preferred over another. For example, while wet chemical techniques may ultimately provide the best sensitivity for open-ocean applications, such sensors will be limited by their longevity in the field and may not be applicable to autonomous profilers that are not recovered, due to power usage and analytical throughputs incompatible with profiling rates (i.e., Argo floats). In this regard, recent developments in analytical chemistry (novel ligands, fluorophores, ionophores, biosensors, miniaturized methods) should be regularly evaluated for their oceanographic potential.

The development of the discussed technologies are of great benefit to society as they will allow an ever greater understanding of ocean and climate feedbacks associated with the input and cycling of trace elements in the ocean. Ocean sampling programs such as GEOTRACES are vastly improving the understanding of dynamics of trace elements and in many instances allow understanding and identification of processes for the first time, in addition to prompting reconsideration of historical paradigms (e.g., Resing et al., 2015). This is largely due to the collaborative nature of these projects that make concurrent observations of multiple trace elements and relevant biogeochemical data over large sections of the world's ocean. These large-scale discrete measurements also provide much desired information on trace metal sources and sinks. However, these ocean sections do not provide a full measure of spatial variability and no measure of temporal variability that we expect *in situ* sensors to provide.

Understanding trace metal dynamics has a wide range of applications, including improving our understanding of oceanic water mass circulation, surveying, and understanding toxic metal plumes and algae. Spatial and temporal observations by micronutrient metal sensors will facilitate significant improvements of numerical models that predict carbon uptake and export to the deep ocean, and thus will provide a better understanding of the role of the ocean in regulating climate. Trace metals are also of societal concern, as they may reflect pollution and in some cases their presence may be detrimental to the base of the food web. Such pollution can occur in coastal regions, as well as the open ocean through dust deposition. By understanding the variability of trace metals we can better understand their impacts on phytoplankton species composition, including the presence of harmful algae blooms. Ultimately, ecosystem management will be better informed by the addition of high-quality data that is rapidly produced and readily available on meaningful time scales.

AUTHOR CONTRIBUTIONS

MG coordinated with all co-authors with regard to the structure and contents of this review manuscript and led the writing effort. All co-authors contributed to a preliminary outline supplied by MG, to the writing and editing of previous versions of this manuscript, and gave final approval for publication. AT compiled the global database of dissolved measurements in the ocean that are used to create **Figure 1**.

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Challenges and Prospects in Ocean Circulation Models

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We revisit the challenges and prospects for ocean circulation models following Griffies et al. (2010). Over the past decade, ocean circulation models evolved through improved understanding, numerics, spatial discretization, grid configurations, parameterizations, data assimilation, environmental monitoring, and process-level observations and modeling. Important large scale applications over the last decade are simulations of the Southern Ocean, the Meridional Overturning Circulation and its variability, and regional sea level change. Submesoscale variability is now routinely resolved in process models and permitted in a few global models, and submesoscale effects are parameterized in most global models. The scales where nonhydrostatic effects become important are beginning to be resolved in regional and process models. Coupling to sea ice, ice shelves, and high-resolution atmospheric models has stimulated new ideas and driven improvements in numerics. Observations have provided insight into turbulence and mixing around the globe and its consequences are assessed through perturbed physics models. Relatedly, parameterizations of the mixing and overturning processes in boundary layers and the ocean interior have improved. New diagnostics being used for evaluating models alongside present and novel observations are briefly referenced. The overall goal is summarizing new developments in ocean modeling, including: how new and existing observations can be used, what modeling challenges remain, and how simulations can be used to support observations.

Keywords: ocean circulation, model, parameterization, climate, ocean processes

1. INTRODUCTION AND SCOPE

The ocean circulation is a critical part of modeling the overall earth system (Chassignet et al., 2019). The oceans are the major reservoir of thermal energy important for climate sensitivity and thermosteric sea level rise (Flato et al., 2013; Palmer et al., 2018), and ocean and ice modeling is increasingly important as weather forecasts in polar and marine climates are extended (Saha et al., 2014; Belcher et al., 2015; Hewitt et al., 2017). The ocean is a primary reservoir for anthropogenic carbon (Khatiwala et al., 2009, 2013), and the oceans contain and affect many important ecosystems and resources for society.

The equations for oceanic motions have been long known (Navier, 1822; Laplace et al., 1829; Stokes, 1845; Onsager, 1931), and subtleties of seawater thermodynamics are also understood (IOC et al., 2010). At present only the ACCESS (MOM5 ocean) and the IPSL-CM6 (NEMO ocean model) have implemented and plan operational use in CMIP6 of the new TEOS-10 equation of state with the exception of the preformed salinity. Note that other modeling centers using MOM and NEMO are not using TEOS-10 for CMIP6. Appendix D of Griffies et al. (2016) features a detailed discussion of present equation of state considerations for modeling, but also state, "there remain unanswered research questions raised by IOC et al. (2010), in particular regarding the treatment of salinity. For CMIP6, we cannot impose strict standards defining what it means to be 'TEOS-10 compliant' when research remains incomplete."

However, the fluid and thermodynamics equations are not yet directly useful, as their discretization without further approximations and parameterizations would require computers about 10 billion times faster and bigger in storage than present supercomputers. These remain about two centuries in the future (Fox-Kemper et al., 2014; Fox-Kemper, 2018), see especially the figure illustrating scaling behavior of CMIP models in (Fox-Kemper et al., 2014)[1].

Thus, numerical and parameterization improvements will continue to define the state of the art in ocean circulation modeling, in concert with integration and co-analysis of observations. Unlike nature, a computer model rarely indicates if processes are left out; it simply provides an incorrect answer. Experiment and observation are how model biases and unrepresented processes are revealed. Furthermore, forecast and state estimation systems are an increasingly valuable tool in providing context and inferences from observations. These tools expand the reach of observations and can improve observation plans, but they rely on the fidelity of their underlying model.

This article is divided into 9 sections covering: (1) introduction; (2) equations, numerics, and discretization; (3) coupled ocean-cryosphere modeling including particularly sea ice and ice shelves; (4) coupled ocean-atmosphere modeling; (5) coupled ocean-surface wave modeling; (6) ocean modeling parameterizations; (7) ocean model diagnosis and evaluation; (8) novel applications of ocean models; and (9) what to expect by 2030, including an assessment of the Griffies et al. (2010) prediction of ocean modeling improvements since 2010. The emphasis throughout is on improvements over the last decade of modeling.

2. EQUATIONS AND DISCRETIZATION OF OCEAN MODELS

The continuum equations of motion for seawater are known (Müller, 2006). However, present ocean models tend to make the Boussinesq, traditional and hydrostatic approximations in addition to discretizing the continuum equations and parameterizing unresolved processes (Fox-Kemper, 2018).

2.1. Vertical Discretization

As of Griffies et al. (2010), three primary approaches to vertical discretization in ocean models were typical: z-coordinate models, which discretize the geometric distance below the geoid as a vertical coordinate; σ-coordinate models, which scale the distance between the sea surface and the terrain into discrete intervals; and isopycnal-coordinate models where vertical discretizations are based on the density stratification. At that time, hybrid vertical coordinate models existed, but the term "hybrid" had multifarious meanings: to some it denoted a linear combination of two or more conventional coordinates (Song and Haidvogel, 1994; Ezer and Mellor, 2004; Barron et al., 2006) or to others it was a truly generalized coordinate, i.e., aiming to mimic different types of coordinates in different regions (Bleck, 2002; Burchard and Beckers, 2004; Adcroft and Hallberg, 2006; Chassignet et al., 2006; Song and Hou, 2006).

This century significant advances in ocean and atmospheric model numerics have occurred by integrating ideas from Arbitrary Lagrangian-Eulerian (ALE) numerical approaches. Adcroft and Hallberg (2006) classify generalized coordinates ocean models as either Lagrangian Vertical Direction (LVD) or Eulerian Vertical Direction (EVD) models. In LVD models, the continuity (thickness tendency) equation is solved forward in

[1] Historically, from the Intergovernmental Panel on Climate Change (IPCC) reports FAR (First Assessment Report) to AR6 (Sixth Assessment Report) the median-resolution and highest-resolution IPCC-class atmosphere-ocean coupled models has increased exponentially, doubling every 12.5 and 7.5 years, respectively. However, if the models for AR6 are left out, the doubling rate is revealed to have been about 10% faster in preceding reports: 10.2 and 6.9 years, respectively. This indicates a slow-down in recent ocean model resolution improvements.

time throughout the domain, while an Arbitrary Lagrangian-Eulerian (ALE) technique is used to re-map the vertical coordinate and maintain different coordinate types within the domain (HYCOM: Bleck, 2002; MOM6: Adcroft and Hallberg, 2006) . In contrast, EVD models use the continuity equation to diagnose the velocity crossing the coordinate surfaces, with examples being the $z-$coordinate models of Bryan (1969), Cox (1984), and Pacanowski et al. (1991) and successors (Smith et al., 2010); $\sigma-$coordinate models like Haidvogel et al. (2008), and generalized EVD approaches facilitating a variety of vertical coordinates like MOM5 (Griffies, 2012), MPAS (Ringler et al., 2013), and NEMO (Gurvan et al., 2017).

The added features of these improved modeling platforms provide the opportunity to increase the model time step (via ALE removal of the vertical CFL), reduce spurious numerical mixing (via ALE remapping to continuous isopycnal coordinates), and directly simulate freshwater addition and removal at the ocean surface (enabled in both LVD and EVD through replacing the rigid lid approach of Bryan (1969) with a free surface). Recent examples of successful applications of these techniques are Hofmeister et al. (2010), Leclair and Madec (2011), Petersen et al. (2015), and Zanowski et al. (2015).

2.2. Horizontal Discretization

Traditionally, ocean models have relied on finite difference or finite volume schemes based on staggered rectilinear grids and the hydrostatic approximation which aided in accuracy and conservation of key properties (Arakawa and Lamb, 1977), but newer approaches enable moving away from these simpler schemes.

2.2.1. Structured Meshes

Nesting of rectilinear structured models–particularly ROMS (Shchepetkin and McWilliams, 2005), NEMO-AGRIF (Debreu et al., 2008) and the MITgcm (Adcroft et al., 2008)–have shown the utility of being able to simultaneously represent small-scale processes and also large basins. Many studies of submesoscale dynamics have taken this approach (e.g., Capet et al., 2008; Gula et al., 2016), recently focusing on air-sea coupling on small scales (Seo et al., 2009; Small et al., 2015; Renault et al., 2016b). A few global and basin-scale simulations with resolution near $1/50^o$ are approaching submesoscale resolution throughout the domain e.g., HYCOM (Chassignet and Xu, 2017); MITgcm (Qiu et al., 2018); and an ongoing effort using NEMO.

2.2.2. Unstructured Meshes

Recent progress in developing unstructured models such as ADCIRC (Luettich and Westerink, 2000; Dietrich et al., 2012), FESOM (Wang et al., 2014; Sidorenko et al., 2015; Danilov et al., 2017; Wang Q. et al., 2018), FVCOM (Chen et al., 2003), ICON (Korn, 2017), MPAS (Ringler et al., 2013), and SLIM (Delandmeter et al., 2018; Vallaeys et al., 2018) is making multi-resolution approaches more flexible and natural. One challenge is that new users find it difficult to write analysis software, and modeling centers are addressing this problem through the development and distribution of analysis packages in higher-level languages such as Python and Matlab. A second challenge is the lack of well-tested scale-aware and flow-aware parameterizations capable of transitioning between coarse-resolution and fine-resolution (Haidvogel et al., 2017).

2.2.3. Hydrostatic Approximation

Traditional ocean modeling has relied on the hydrostatic approximation, which makes accurate estimation of the pressure field, and thus geostrophic flows, easier. This approximation is valid when the aspect ratio of the motions are shallow, which can be guaranteed by using shallow grid cells or found in high stratification. In contrast, oceanic boundary layer Large Eddy Simulations (e.g., McWilliams et al., 1997) cannot use the hydrostatic approximation. As horizontal resolutions increase, nonhydrostatic effects become increasingly strong and presently are detectable at the small-scale end of the submesoscale (Mahadevan, 2006; Hamlington et al., 2014; Suzuki et al., 2016) and in deep convection (Marshall et al., 1997). Few ocean circulation models presently have nonhydrostatic capability. Boundary layer LES models have always been nonhydrostatic (e.g., McWilliams et al., 1993), but some ocean circulation models– beginning with PSOM (Mahadevan et al., 1996a,b) and the MITgcm (Marshall et al., 1997), but more recently SUNTANS (Fringer et al., 2006) and CROCO-ROMS (Cambon et al., 2018)– have this capability.

2.3. Numerical Artifacts

2.3.1. Stability, Conservation, Convergence, and Performance

A good numerical scheme can be shown to converge as resolution increases to the solution of the partial differential equations it approximates discretely. Great numerical schemes converge efficiently, using fewer processor operations, less communication, and/or less memory.

Convergence requires both consistency (i.e., the discrete equations represent the correct differential equations) and stability (i.e., the numerical scheme does not "blow up" upon iteration) (Lax and Richtmyer, 1956). Model crashes can be very costly in a supercomputing setting where model initialization costs are large, so robust stability is a requirement for ocean model numerics. The easiest numerical schemes to implement, and thus most widely used, are explicit methods which are typically conditionally stable: stability occurs only for sufficiently small time steps. Unconditional stability, such as from some implicit schemes, can be desirable but can come at the expense of accuracy. Although unconditional stability allows very large time steps, processes faster than the time step will be neglected or poorly simulated resulting in inconsistency. Griffies and Adcroft (2008) summarize the variety of time step constraints encountered in ocean circulation modeling.

Consistency is easily demonstrated in simple cases, but frequently is difficult to assess in complex oceanic flows. Some methods may be very well-suited to particular phenomena, such as fronts, while another may be better for general purposes but fail at fronts. Most equations of motion are budgets for conserved properties. Mimetic numerics offer the means to exactly conserve discrete analogs of the continuum budgets and continuous equation symmetries–such as conservation laws, solution symmetries, and the fundamental identities and theorems of vector and tensor calculus–thus mimetic methods frequently assure consistency (Hyman et al., 2002). Spectral schemes, on the other hand, are difficult to make conservative and may spontaneously generate local extrema, but have high order accuracy. Spectral element, discontinuous Galerkin methods, and related schemes seek a happy medium of mimicry and differential accuracy.

Recent improvements in numerics have greatly enhanced the stability of ocean climate models. ALE schemes have shown better stability, parameterizations have led to improved stability (Fox-Kemper and Menemenlis, 2008), and Newton-Krylov and implicit schemes have improved (Nadiga et al., 2006; Lindsay, 2017). Newton-Krylov approaches have also increased the efficiency of spinning up the deep ocean to simulate important tracer distributions (Bernsen et al., 2008; Khatiwala et al., 2009; Bardin et al., 2014).

Scheme efficiency differs with computer architectures. At present, most ocean modeling is carried out on systems featuring hundreds to thousands of computing cores (CPUs), organized with shared memory and extremely rapid communications among nodes with roughly a dozen cores and somewhat slower inter-node communication. Graphical processing units (GPUs) are much faster and power-efficient than normal cores, but are not as general-purpose, do not perform as well with branches, and are typically limited in memory. Cloud computing is an exciting innovation, offering ready access to diverse and affordable heterogeneous hardware, but communication over the internet is much slower than among nodes in a supercomputer so new software engineering and algorithms are needed (Hamman et al., 2018).

2.3.2. Spurious Diapycnal Mixing

A classic ocean numerics challenge is respecting the tiny diapycnal diffusion acting on tracers in the presence of rapid advection and diffusion oriented along neutral direction (Veronis, 1975; Griffies et al., 2000). This *spurious mixing problem* is exacerbated in the mesoscale eddying regime emerging in ocean climate models. The numerical difficulty arises from the cascade of tracer variance to the grid scale engendered by transient eddy features in an advectively dominant flow. Numerical tracer advection operators must satisfy two competing goals: avoiding false extrema manifest as grid-scale noise *and* minimizing spurious diapycnal mixing.

There are two sources of spurious mixing: numerical mixing associated with vertical advection across the model vertical coordinate, and numerical mixing in the horizontal direction due to lateral processes where the inclination of isopycnals projects into a diapycnal effect (Gibson et al., 2017). Isopycnal coordinates minimize both sources (Bleck, 1998) for regions where isopycnals approximate neutral directions. However, purely isopycnal models are limited in other ways such as in the representation of weakly-stratified boundary layers, nonhydrostatic flows, and overturning, as well as in capturing the full suite of watermass transformations (IOC et al., 2010; McDougall et al., 2014).

Reducing spurious mixing in Eulerian vertical coordinate models requires high order accuracy of the numerical advection operators in all three dimensions. This approach can be sufficient for idealized model studies (Griffies et al., 2000; Hill et al., 2012); however, the accuracy of advection operators is degraded in limiting fluxes to avoid false tracer extrema in realistic models. Griffies et al. (2000) and Ilicak et al. (2012) point to the importance of tuning lateral friction to ensure that all admitted flow features are properly resolved by the chosen grid spacing, thus allowing for the reduced reliance on flux limiters. Bachman et al. (2017a) show that physically-based, scale-aware parameterizations can achieve the needed flow regularization if suitably matched to the class of flow being simulated.

The ALE algorithm provides a means to use arbitrary vertical coordinates, thus offering a promising middle ground between the isopycnal layer approach and the Eulerian approach (Bleck, 2002, 2005). The general strategy is to make use of a high order vertical remapping scheme (White and Adcroft, 2008; White et al., 2009) within a continuous isopcynal coordinate interior, thus allowing for the full suite of nonlinear equation of state effects while retaining the integrity of transport along neutral directions. Further work is needed to fully assess the ability of ALE to resolve the spurious mixing problem in the presence of an active eddying flow while retaining other capabilities needed for realistic ocean modeling (e.g., high latitude processes).

2.3.3. Implicit Dissipation

In order to maximize stability, many schemes are designed to tend toward dissipation of energy or tracer variance when numerical errors are inevitable. Dissipative artifacts are typical byproducts in this class of numerical schemes, including upwinding, monotonic, flux-limiting, and shock-capturing schemes. This implicit dissipation can add to physical parameterizations of diffusivity leading to overestimation (Bachman et al., 2017a). For this reason, it is sometimes necessary to select the parameterizations and numerics in tandem, thereby selecting numerics reducing the implicit dissipation if a dissipative parameterization is expected to be sufficient (Bachman et al., 2017a), or a dissipative numerical scheme if explicit parameterizations are unknown (Shchepetkin and McWilliams, 2005).

3. OCEAN-CRYOSPHERE MODELING

3.1. Sea Ice

Sea ice is an important component of an state-of-the-art ocean–ice modeling framework. It strongly modifies atmosphere–ocean interactions inciting important climate feedbacks. Griffies et al. (2010) did not address sea ice, but recent progress in those models induced a treatment following Smith et al. (2018), who divides to sea ice studies into four subtopics: (1) sea-ice fractures and cracks, (2) sea-ice interactions with solids, (3) sea-ice interactions with fluids, and (4) multi-scale sea-ice modeling. Large- and mesoscale resolutions and ice-ocean coupling are the topic here, which make the recent findings on topics 3–4 most important (see also Lemieux et al., 2018). Effects on smaller than geophysical scales are neglected here, such as ice micro-structure and off-shore structures in ice-covered oceans.

3.1.1. Sea-Ice Thickness Distribution

Multiple category sea-Ice Thickness Distribution (ITD) parameterization has become standard in large-scale sea-ice modeling (Hunke, 2010; Rousset et al., 2015). It better represents the seasonal cycle of sea-ice volume evolution, particularly the spring melt, when compared to single category parameterization (Uotila et al., 2017). The nonlinear dependence of heat conduction through vertical layers of ice and snow, and thus the thermodynamic growth rate at the bottom layer, also makes the implementation of ITD necessary in multi-level models (Castro-Morales et al., 2014). Hunke (2014) conclude that the commonly-used five ice thickness categories are not enough to accurately simulate ice volume.

3.1.2. Sea-Ice Salinity

Following developments such as Vancoppenolle et al. (2009), Turner and Hunke (2015) develop a sea-ice model with a fully prognostic and variable ice salinity vertical profile. After adjustments of gravity drainage parameterization, their model produced good agreement with salinity observations being also sensitive to the melt-pond area and volume. The new thermodynamics produced realistically thicker Arctic ice than the old, constant salinity thermodynamics.

3.1.3. Melt Ponds

A melt pond theory was developed by Flocco et al. (2010) and incorporated in a state-of-the-art sea-ice model with an ITD. They recommend the inclusion of melt ponds in sea-ice models with increased number of thin ice thickness categories. Simulation based results by Kim et al. (2018) indicate that the salinity of melt ponds may control their heat balance–an aspect not yet taken into account in model parameterization.

3.1.4. Ice-Waves Interaction

Bennetts et al. (2015) implement an idealized wave–ice interaction model taking into account both wave-induced ice fracture and wave attenuation due to ice floes. Bennetts et al. (2017) analyze wave-induced breakup of Antarctic ice using a sea-ice model that is a common component of many climate models. Williams et al. (2017) couple a waves-in-ice model with a sea-ice model and studied the effects of ocean surface wave radiation stress compared to wind stress. The wave scattering in the Marginal Ice Zone (MIZ) has similar properties for a large range of ice types and wave periods which allows the computation of temporal evolution of wave packets through the MIZ (Meylan and Bennetts, 2018). As sea-ice models poorly represent ice break-up and formation with ocean waves, satellite observations are particularly beneficial in quantifying wave impacts (Stopa et al., 2018).

3.1.5. Sea-Ice Floe Size Distribution (FSD)

A sea-ice floe size distribution (FSD) improves process precision, mainly for ice–waves interactions in the MIZ and seasonal ice zones. Zhang et al. (2015) develop a theory where FSD and ITD jointly evolve taking into account FSD changes due to ice advection, thermodynamic growth, lateral melting and wave-induced ice fragmentation. Horvat and Tziperman (2015) develop and test idealized cases of a model for the evolution of the joint FSD and ITD, including lateral freezing and melting, mechanical interactions of floes, and floe fracturing by waves. Horvat et al. (2016) show that sea-ice melting-related processes at floe boundaries provoke ocean mixed-layer submesoscale eddies that transport heat horizontally. They emphasize that these processes, FSD thermodynamics, and the associated ocean eddies are neglected in present climate models. Roach et al. (2018) argue that FSD is important for the accurate simulation of polar oceans and climate. They developed a model where floe sizes are prognostic and depend on new ice formation, welding of floes in freezing conditions, lateral growth and melt, and wave fracture of floes.

3.1.6. New and Updated Rheologies

Ice dynamics modeling has progressed in the last decade. Losch and Danilov (2012) compare solutions for the sea-ice momentum equation based on implicit viscous-plastic (VP) and explicit elasto-viscous-plastic (EVP) methods, and found rather different solutions, yet EVP solutions do converge toward the VP results as time steps approach zero. Bouillon et al. (2013) revisit EVP and confirm unsatisfactory convergence and provide adjustments for the internal ice stress to filter out artificial linear stress features. Kimmritz et al. (2016) continue to test the stability and convergence of the modified EVP method and recommend adaptive variation of modified EVP scheme parameters. Lemieux et al. (2014) develop and implement a new time-stepping method so that sea-ice concentration and thickness evolve implicitly. The new scheme improves tenfold the accuracy of long time steps and is computationally five times more efficient.

Progress has been made in implementing anisotropic rheology in the pack ice field. Hunke (2014) find that an anisotropic rheology slows the ice motion by increasing shear stress between floes, while variable air–ice and ice–ocean drag coefficients lead to thinner ice. An elastic anisotropic plastic rheology produces sharper ice field deformation features and follows a more realistic power law strain rate than the commonly adapted EVP rheology (Heorton et al., 2018).

Arctic sea ice change over the past few decades represents a new dynamical regime with more mobile ice and stronger deformation, challenging traditional sea-ice models. To address this, Rampal et al. (2016) develop a Lagrangian sea-ice model with an elasto-brittle rheology and thermodynamics with healing capability for extreme fracturing. Their new model captures sea-ice drift and deformation, and the seasonal cycles of ice volume and extent improve. Rabatel et al. (2018) test the Lagrangian model of Rampal et al. (2016) for probabilistic forecasting in hindcast mode with uncertain winds driving the ice motion. They show that the Lagrangian sea-ice model (Rampal et al., 2016) is a viable alternative for sea-ice forecasting.

3.1.7. Atmosphere–Ice–Ocean Coupling

Tsamados et al. (2014) implement and test variable atmospheric and oceanic drag parameterizations that take into account ice surface features such as pressure ridges and melt pond edges in ice-only models. As drag coefficients are coupled to the sea-ice properties, they evolve temporally and spatially. Castellani et al.

(2018) implement variable air-ice and ice-ocean drag coefficients but in an ocean-ice model. Drag coefficients that vary result in faster moving, thinner and more realistic Arctic sea ice. In the ocean, variable drag coefficients deepen the mixed layer and alter surface salinity and temperature. Barthélemy et al. (2016) present an ITD based sub-grid-scale representation of momentum and buoyancy fluxes between ocean and ice. This effort separates estimates of convection and turbulent mixing by ice thickness category, weighted by fraction per grid cell. For long mixing time scales, the ITD-dependent mixing decreases the under-ice mean mixed layer depth and decreases oceanic heat flux melting ice in summer.

Coupled climate models typically treat sea-ice and the ocean as distinct components that only exchange information via a coupler, and they often lag the application of forces on the ocean relative to the ocean state upon which they are based. This approach has the advantage of permitting the separate development of coupler, ocean, and sea-ice model software. However, key aspects of the rapid sea ice and ocean dynamics are fundamentally coupled, and treating the ice and ocean as disconnected components can lead to coupled numerical instabilities associated with coupled gravity waves and ice-ocean stresses (Hallberg, 2014). To avoid these instabilities, coupled models may be forced to take shorter coupling time steps or make unphysical approximations. A more intimate coupling of the ice and ocean dynamics could avoid these instabilities and improve computational efficiency and physical fidelity.

3.1.8. Model Calibration

Massonnet et al. (2014) optimize sea-ice model parameter values with an ensemble Kalman filter method by calibrating the model against sea-ice drift observations in the Arctic. This optimisation resulted in a significant bias reduction of simulated ice drift speed and slight improvement in ITD. Losch et al. (2010) compare different numerical solvers for dynamics and thermodynamics used in sea-ice models and found that the choice of the dynamic solver has a considerable effect on the solution. Hunke (2010) adjusts many sea-ice model parameters to obtain the most realistic representation of global sea ice. In addition to albedo, which is a commonly used tuning parameter, many other parameters related to ice thermodynamics and dynamics can have equally large effect on global sea-ice distribution. More extensive adjustments on an ocean-ice model by Uotila et al. (2012) show that the sea-ice model adjustments matter most in summer, while in winter external factors dominate the evolution of sea ice. Recently, Sumata et al. (2018) used more than two decades of sea ice concentration, thickness, and drift data including their uncertainties in a cost function, to optimize 15 dynamic and thermodynamic process parameters with a genetic algorithm.

3.1.9. Other Developments

Exciting progress has also been made in other fields of sea-ice modeling during the last 10 years than listed above. For example, discrete element modeling of sea ice (Herman, 2016), parameterization of snow thermodynamics (Lecomte et al., 2011) and wind-blown snow drift (Lecomte et al., 2015), and landfast ice implementations (Lemieux et al., 2015) can now be treated in more advanced ways in ocean-ice climate models. There are also different subgrid issues at hand when modeling sea ice. Recent work on ice rheology (Feltham, 2008), wave-ice interactions (Williams et al., 2013), and submesoscale-floe size interactions (Horvat and Tziperman, 2017) are making their way to implementation. These improvements to ocean-ice climate model configurations are expected to increase their realism. Future work will assess the benefits of complexity in sea-ice models and enhanced resolution for climate projections. Satellite and *in situ* observations of sea ice and its atmospheric and oceanic environment will aid in evaluating the realism of these improvements.

3.2. Ice Shelves and Icebergs

High-latitude precipitation flows to the ocean often via land ice. Accumulation of snow forms ice sheets which flow slowly to the oceans. The land ice stores significant mass which makes understanding the evolution of the ice sheets, and the interaction between land-ice and oceans, paramount to understanding and predicting future sea level. The land ice-ocean boundary is difficult to access and thus poorly observed. Only recently has this interface been modeled and considered for inclusion in climate models. Where glaciers enter the ocean in fjords, there is often injection of melt water in plumes at depth at the base of the glacier (Jenkins, 2011; Straneo and Cenedese, 2015). This configuration is common for Greenland and Arctic glaciers. In the Southern hemisphere, the Antarctic ice sheet feeds floating ice-shelves which form ocean-filled sub-ice shelf cavities. Ice shelves lose mass to the ocean by basal melting, controlled by ocean circulation and properties, or by calving of icebergs (Dinniman et al., 2016; Asay-Davis et al., 2017). The loss of grounded ice is what contributes to sea-level, while the freshwater input to the ocean is determined by the relative flux of basal melt to calving. Basal melting is an *in situ* freshening of seawater while icebergs can carry the freshwater offshore to the open ocean.

Gladstone et al. (2001) develop a model of icebergs trajectories in the ocean. Jongma et al. (2009) couple an iceberg model to an ocean model to examine iceberg-ocean interactions. Martin and Adcroft (2010) make the icebergs an integral part of the hydrologic cycle in a fully coupled model. Systematic improvements of the representation of icebergs and their interaction with the ocean continue (Marsh et al., 2015; Stern et al., 2016; Wagner et al., 2017; FitzMaurice and Stern, 2018). A challenge for modeling of icebergs is to simulate the observed distribution of size and shape. Using satellite altimetry, Tournadre et al. (2016) find a power-law distribution for small icebergs which has subsequently been used as an input to iceberg models. It is not clear whether the distribution is determined by the poorly understood calving process or the subsequent evolution of the icebergs. However, the majority of the iceberg mass flux into the ocean is due to the large and tabular icebergs. Large icebergs (say larger than 10 km) live longer and thus can transport fresh water further offshore but their size is comparable to ocean grid cells and thus the representation as point particles used in many iceberg models becomes a poor approximation. The problem is worse for the giant tabular icebergs which can be 100's of km wide. The detailed distribution and occurrence of giant tabular icebergs is poorly understood and potentially unpredictable and their representation in climate models is an active area of research (Stern et al., 2017).

Sub-ice shelf melting and ice sheet grounding line retreat/advance both amount to a changing ocean geometry, a process difficult to capture—and not represented—by most current-generation GCMs, but one that carries important ocean-ice feedbacks (thinning ice shelves reduce ice sheet buttressing, while grounding line migration impacts the ice sheet's stress balance). Progress has nevertheless been made, beginning with approaches referred to as *discontinuous* (Gladish et al., 2012; Goldberg et al., 2012a,b; De Rydt and Gudmundsson, 2016; Mathiot et al., 2017). More recently, approaches have employed either *asynchronous* or *synchronous* coupling. In the former case, information between the components are exchanged once every few ice time steps (e.g., monthly), during which the ocean geometry is held fixed. Moving from one fixed ice-shelf topography to another at the coupling step leads to continuity issues with mass, heat, salt, and momentum in the ocean that have to be solved with *ad-hoc* techniques (Asay-Davis et al., 2016; Seroussi et al., 2017). In the latter case, mass continuity is evolved at the ocean model's time step, thus ensuring that the freshwater (volume) flux translates conservatively into a corresponding change in geometry (vertical coupling). Furthermore, ice sheet retreat or advance (horizontal coupling) is achieved through maintenance of a thin or massless ocean layer below the (grounded) ice sheet, controlled by a porous flux (Goldberg et al., 2018; Jordan et al., 2018). Faithful representation of glacier-fjord (Greenland) and ice shelf-ocean (Antarctica) interactions remains among the premier challenges in climate modeling in support of sea level science.

3.3. Global Ocean/Sea-ice Simulations Based on CORE-I, CORE-II, and JRA55-do

The Coordinated Ocean-sea ice Reference Experiments (CORE) provide a framework for global ocean/sea-ice model simulations and inter-comparison. The CORE-I simulations documented by Griffies et al. (2009) made use of the atmospheric state from Large and Yeager (2004) to derive their bulk formula forcing. Even though all models made use of the same atmospheric state, the CORE-I simulations revealed previously unknown sensitivities across a suite of global ocean/sea-ice models. In the years since its design, CORE-I has proven to be a useful framework for model assessment and model-model comparison. It has thus become a standard method to develop and to assess global ocean/sea-ice model configurations.

Large and Yeager (2004) developed an artificial "Normal Year Forcing" (NYF) for indefinitely repeating the forcing year. This approach simplifies the task of spinning up a model to quasi-equilibrium and for measuring model sensitivity to changes in numerics and physics. However, the NYF precludes direct comparison of simulations to real-time data such as that increasingly produced from observational campaigns. These limitations led the modeling community to embrace the CORE-II interannual atmospheric state of Large and Yeager (2009). This dataset extends from 1948 to 2007 and forms the basis for nine papers that assess the physical integrity of roughly 20 global ocean/ice models: two papers focused on the North Atlantic circulation (Danabasoglu et al., 2014, 2016), one on sea level (Griffies et al., 2014), three on the Arctic (Ilicak et al., 2016; Wang et al., 2016a,b), two on the Southern Ocean (Downes et al., 2015; Farneti et al., 2015), and one on the Pacific (Tseng et al., 2016). CORE-II has proven to be a useful means to benchmark global model simulations against observational measures, thus engaging the observational community in a manner unavailable from CORE-I. This collaborative assessment of global simulations is essential for improving both the models and the observations, particularly in a world where datasets available from simulations and observations are beyond the ability of a single research group to master.

The success of the CORE-II studies has left the modeling and observational community wanting more. It also revealed the limitations of the Large and Yeager (2009) dataset, most notably termination in year 2009 and by today's standards a relatively coarse space and time resolution. To address this community need, Tsujino et al. (2018) have produced the next-generation global ocean/sea-ice forcing product known as JRA55-do, building from the Japanese reanalysis (Kobayashi et al., 2015) and inspired by the bias correction approaches of Large and Yeager (2009). JRA55-do offers refined temporal and spatial resolution, plus the capability of being extended consistently into the future as the atmospheric reanalysis is extended. Consequently, it is being used for the CMIP6 Ocean Model Intercomparison Project (OMIP) (Griffies et al., 2016; Orr et al., 2017). We thus anticipate that JRA55-do will soon become the community standard.

4. OCEAN-ATMOSPHERE MODELING

4.1. Fluxes

The forcing products for ocean-ice experiments differ from the behavior observed in coupled models (Bates et al., 2012b) as atmospheric models have biases of their own and because the coupled system can possess positive feedbacks that accentuate ocean and ice model issues and negative feedbacks that limit basin-scale coupled model drift. Even so, a critical application of ocean and sea ice models is their use as components of earth system models for the study of detection and attribution of anthropogenic climate change impacts, as well as tools for designing adaptation, mitigation, and geoengineering strategies. Hence, the fidelity of the coupled model behavior is paramount. This raises the question of whether it is more beneficial to evaluate and tune the ocean and ice components in forced settings, such as the CORE forcing paradigm, vs. in coupled mode. Given underlying biases in atmospheric forcing and the possibility of introducing compensating errors in coupled mode, the optimal strategy is most likely to require both forced and coupled approaches in tandem.

4.2. Boundary Layers

Atmospheric model parameterizations of convection and turbulence, as in the ocean, are simplified representations of complex interactions. The added complexity of water vapor phase changes, clouds, and cloud and aerosol interactions affecting absorption and reflection of radiation make many aspects of atmospheric parameterizations different from oceanic parameterizations. The basic turbulence closures of the dry atmospheric boundary layer and the upper ocean boundary layer (see section 6.2) have many similarities and often common origination (e.g., Troehn and Mahrt, 1986; Large et al., 1994). Large eddy simulation software is commonly shared between the two fluids (e.g., Sullivan and Patton, 2008) and many concepts and discoveries have been transferred between the fields.

5. SURFACE WAVE MODELING

With the exception of nearshore modeling, such as implementations of ADCIRC (Dietrich et al., 2012) and ROMS (Rong et al., 2014) coupled to WaveWatch-III (Tolman, 2009) or SWAN (Booij et al., 1997), surface gravity waves are typically not explicitly included in ocean circulation modeling. However, this attitude is changing with the growing awareness of the importance of wave breaking effects and wave-driven mixing (Melville, 1996; Babanin and Haus, 2009; Huang and Qiao, 2010), such as Langmuir turbulence (Belcher et al., 2012; D'Asaro et al., 2014; Li et al., 2016) and the closely related non-breaking surface-wave-induced turbulence (Qiao et al., 2004, 2016), and variations in sea state and surface roughness effects on air-sea momentum coupling (Kukulka et al., 2007; Chen et al., 2018), sea spray aerosol production (Long et al., 2011) and sea spray effects on typhoon forecasts (Zhao et al., 2017), gas transfer (Miller et al., 2009), wave effects on currents (McWilliams and Fox-Kemper, 2013; Suzuki et al., 2016) and current effects on waves (Gallet and Young, 2014; Ardhuin et al., 2017), wavy Ekman layers (McWilliams et al., 2012), and wave impacts on a variety of other climate processes (Cavaleri et al., 2012). Wave models have long been used in numerical weather prediction systems (Janssen et al., 2002). The recently released CESM2 includes an implementation of the WaveWatch-III model as a new component of the climate modeling system (Li et al., 2016), the newest GFDL boundary layer mixing schemes include Langmuir mixing using a statistical representation of waves (Li et al., 2017) and versions of the ACCESS model (Bi et al., 2013), GFDL model (Fan and Griffies, 2014), and FIO model (Qiao et al., 2013) are coupled to surface wave models.

6. OCEAN PARAMETERIZATIONS

6.1. Mesoscale

The class of ocean parameterizations most characteristic of the challenges particular to the ocean are those describing the oceanic mesoscale and their eddying features. Transient ocean mesoscale eddies are ubiquitous, contain more energy than the time mean ocean currents, and strongly affect critical large-scale behavior such as ocean heat uptake, meridional transport, and carbon storage. Their effects are sufficiently profound that modest changes to mesoscale parameterizations (or mesoscale-resolving models) frequently have a larger effect on ocean climate sensitivity than the total effect of other classes of parameterizations. In some problems, such as the response of the Southern Meridional Overturning Circulation to changing winds, the treatment of mesoscale eddy effects qualitatively affects the answer (Ito and Marshall, 2008; Bishop et al., 2016), although well-crafted parameterizations can capture this effect correctly (Gent, 2016; Mak et al., 2017; Marshall et al., 2017).

There are two main effects of mesoscale eddies that are parameterized: eddy-induced advection and eddy-induced diffusion. The primary example of the former is the Gent and McWilliams (1990) scheme, while the latter is normally treated using an anisotropic diffusion tensor aligned according to neutral directions (Redi, 1982). It is frequently convenient in both parameterization (Griffies, 1998) and diagnosis (Bachman et al., 2015) to treat both effects simultaneously as the antisymmetric and symmetric parts of one coefficient tensor in a flux-gradient relation. This basic formulation is almost universally used, but there are major differences in approach in the specification of this coefficient tensor and how it varies in space, with resolution, and as the flow varies. There are reasons to believe it should depend on eddy energy (Eden and Greatbatch, 2008; Marshall and Adcroft, 2010; Marshall et al., 2017), as well as orient itself appropriately along the stratification (Nycander, 2011; McDougall et al., 2014). Likewise, kinematic theory and modeling suggests that the eddy-induced advection and diffusion should be closely related (Dukowicz and Smith, 1997; Bachman and Fox-Kemper, 2013), but not in a trivial manner when there is structure in the vertical stratification (Smith and Marshall, 2009; Abernathey et al., 2013). Additionally, care is required as boundaries are approached and the stratification approaches mixed layer values (Danabasoglu et al., 2008; Ferrari et al., 2008, 2010).

One way to avoid strong dependence on the parameterization of the mesoscale is to resolve the largest mesoscale eddies, which reach near 25 km in the middle latitude open ocean. However, it is rare that mesoscale eddies are well-resolved over all of the world, given the variations in the Coriolis parameter and stratification (Hallberg, 2013). Furthermore, higher vertical modes require finer horizontal resolution, which eventually blends into the submesoscale regime (Boccaletti et al., 2007). Thus, subgrid schemes that expect only part of the mesoscale eddies to be resolved are required as model grid spacing reaches 25km and finer. One approach is to adapt turbulent cascade theory as Smagorinsky (1963) did for energy, only here apply it to the 2D enstrophy (Leith, 1996; Fox-Kemper and Menemenlis, 2008) or quasigeostrophic potential enstrophy (Bachman et al., 2017a). This approach can considerably improve the effective resolution (Soufflet et al., 2016) of eddy-permitting models (Pearson et al., 2017), and is fully flow-aware (i.e., responsive to changing ocean conditions) and scale-aware (consistent across multiple resolutions). Another approach is to introduce new terms in the advection equation that are dispersive or non-Newtonian (Bachman et al., 2018). Under such approaches, the coefficients are highly amenable to flow- and scale-aware treatment (Porta Mana and Zanna, 2014).

Stochastic parameterizations of eddies are also increasing in popularity and sophistication (Grooms and Majda, 2013; Porta Mana and Zanna, 2014; Grooms et al., 2015; Grooms, 2016), although no major climate models use this approach for ocean eddy parameterization yet.

Jansen and Held (2014) introduced a backscatter approach in which a sub-grid scale energy budget is used to inject energy back into a model using a negative, Laplacian eddy viscosity. The approach counters the tendency in some models to dissipate too much energy on the grid scale and increases the effective resolution in both channel configurations (Jansen and Held, 2014; Jansen et al., 2015) and in a shallow water model for a closed basin under double gyre wind forcing (Kloewer et al., 2018). Other approaches arrive at similar results by scaling a positive Laplacian dissipation based on the forward potential enstrophy cascade (Pearson et al., 2017), but this approach requires resolving the whole eddy instability scale (Bachman et al., 2017b). Further work is needed to extend and unify these methods for realistic ocean models at presently affordable resolutions.

6.2. Boundary Layer Mixing

The boundary layers at the surface and bottom of the ocean cannot be ignored, as these layers are where the influence of winds, freshwater, ice, heating and cooling, and relative motion against the solid earth are prescribed. The depth of these layers is directly related to global climate sensitivity (Hasselmann, 1976) and affects weather predictions (Emanuel, 1999). However, because of the proximal forcing, these regions also have distinct stratification–they tend to be largely co-located with the vertically well-mixed mixed layers[2]–and flow–they tend to be characterized by nearly isotropic three-dimensional turbulence rather than stratified or quasi-2D turbulence of the ocean interior. If the turbulence is isotropic and contained within the 10 to few 100 m mixed layers, then the horizontal scale of this turbulence is also only tens to hundreds of meters, and thus this turbulence will not be resolved in global ocean models until well into the twenty-second century. The simplest parameterizations of the boundary layer are just fixed depth regions of increased vertical mixing. However, even early parameterizations included the ability to deepen the boundary layer through entrainment and restratify through surface fluxes (Kraus and Turner, 1967). Major improvements in boundary layer and mixed layer parameterizations have been driven by improved observational compilations of variability of these layers (e.g., de Boyer Montégut et al., 2004; Sutherland et al., 2014).

Boundary layer schemes take the surface fluxes of wind stress or bottom stress, surface cooling or heating, penetrating solar radiation, and then convert these forcing parameters into a profile of turbulent effects. Many schemes result in profiles of scalar mixing diffisivities and viscosity (e.g., Large et al., 1994) which then can be used in the calling model; other second-moment or higher-moment schemes provide fluxes and covariances directly (Mellor and Yamada, 1982). The new boundary layer scheme for climate models of Reichl and Hallberg (2018) combines the energetic constraints of Kraus and Turner (1967) with the possibility for mixed layer gradients and computational efficiency. A software innovation in ocean modeling is the development of software modules containing many different parameterizations in a portable format so that they can be rapidly substituted within a model, or shared across ocean models that all include the module. The Generalized Ocean Turbulence Model [GOTM: Burchard and Bolding (2001)] led the way to modular community boundary layer turbulence systems, capturing both simple schemes and full second-moment schemes. Now in version 5, GOTM is widely used in coastal and process modeling applications. The Community Ocean Vertical Mixing package (CVMix: Griffies et al., 2015a; Van Roekel et al., 2018) is similar, but is specialized to climate modeling applications and emphasizes parameterizations that produce profiles of diffusivity and viscosity. CVMix is implemented in MOM6, POP, and MPAS.

A significant change in boundary layer schemes over the last decade is the awareness of wave-driven mixing, beyond mixing driven just through wave breaking. The theoretical underpinnings of this idea extend back to Langmuir (1938), but modern theory (Craik and Leibovich, 1976; Teixeira and Belcher, 2002), modeling (Denbo and Skyllingstad, 1996; McWilliams et al., 1997), and observations (D'Asaro and Dairiki, 1997; Belcher et al., 2012; D'Asaro et al., 2014) have led to the development of a variety of recent parameterizations of wave-driven turbulence (Harcourt and D'Asaro, 2008; Van Roekel et al., 2012; Harcourt, 2015; Reichl et al., 2016). Their successful implementation in ocean circulation models is a relatively recent occurrence (Fan and Griffies, 2014; Li et al., 2016) because these mixing schemes depend on the wave state, so an ocean surface wave model is needed as part of the coupled system, although in many cases a statistical approximation may be sufficient (Li et al., 2017). Such an approximation, available through CVMix, is surely warranted to assess whether the development cost of coupling the wave model is justified. With care, mixed layer depth and ventilation biases can be significantly improved (Li et al., 2016; Li and Fox-Kemper, 2017). Related theories following different wave-driven turbulence parameterization assumptions have also shown bias reduction in ocean models (Babanin and Haus, 2009; Huang and Qiao, 2010).

6.3. Internal Mixing

Mixing across isopycnal surfaces, although small in magnitude relative to mixing in the surface layer, is an essential component of the global ocean circulation. While earlier models represented diapycnal mixing of tracers as a constant or a depth-dependent function (Bryan and Lewis, 1979), current climate and regional models increasingly attempt to account for the physical processes responsible, allowing mixing to change in response to changing ocean conditions (MacKinnon et al., 2017).

Mixing across isopynal surfaces in the stratified ocean interior is driven primarily by instabilities of sheared flow. For resolved sheared flows, parameterizations based on the resolved Richardson number (Ri) can be used to estimate diapycnal diffusivity. These parameterizations range from diagnostic equations for Ri-dependent diffusivities (Pacanowski and Philander, 1981; Large et al., 1994) to Ri-dependent structure functions in two-equation turbulence closure schemes used in

[2]The technical distinction is that boundary layers are in the process of mixing and so are turbulent whereas mixed layers have already been mixed so are weakly stratified in the vertical.

many regional models (Mellor and Yamada, 1982; Umlauf and Burchard, 2003; Jackson et al., 2008).

Much of the shear responsible for mixing is in the internal wave field, on spatial and temporal scales too small for a climate model to resolve, so that mixing parameterizations based on resolved shear are insufficient. Instead, the diapycnal mixing can be formulated in terms of the global internal wave energy budget (Ferrari and Wunsch, 2009; Eden and Olbers, 2014), with sources of energy from the tides (Garrett and Kunze, 2007), surface winds, and flow over topography (Nikurashin and Ferrari, 2011; Scott et al., 2011) including the important feedbacks of wave drag on the flow (Trossman et al., 2013, 2016), and loss of wave energy to dissipation and mixing by wave-breaking at topopography or through nonlinear wave-wave interactions in the ocean interior. The energy sources, particularly the tidal energy source, are relatively well understood (Bell, 1975; Garrett and Kunze, 2007; Falahat et al., 2014) compared to the sinks. A model of internal tide energy dissipation (St. Laurent et al., 2002) used in several climate models (Danabasoglu et al., 2012; Dunne et al., 2012) represents the local dissipation of internal tides near the wave generation site as a fixed fraction of the energy source, with a vertical distribution which decays exponentially with height above bottom. A similar formulation has been applied to wind-generated near-inertial wave energy, with dissipation decaying with depth below the mixed layer (Jochum et al., 2013), and to lee-waves generated by subinertial flows (Melet et al., 2014). However, the locally dissipated energy fraction is in reality not a constant, but rather depends on the proportion of energy distributed at different wavelengths (St. Laurent and Nash, 2004; Klymak et al., 2010), and hence the small-scale details of the local topography (Lefauve et al., 2015), as well as the effectiveness of latitude-dependent wave-wave interactions such as parametric subharmonic instability (Nikurashin and Legg, 2011; Richet et al., 2018).

The vertical distribution of dissipation due to breaking internal waves also depends on the details of nonlinear interactions, and several new models are attempting a more physical representation of these processes (Polzin, 2009; Melet et al., 2013; Olbers and Eden, 2013; Lefauve et al., 2015). The most difficult component of the internal wave energy budget to represent is the propagation of low-mode waves far from the generation site (Zhao et al., 2016), and the loss of energy from these waves as they encounter different regions of the ocean such as continental slopes (Nash et al., 2007; Martini et al., 2011; Legg, 2014). Several models of low mode wave propagation (Eden and Olbers, 2014; de Lavergne et al., 2016) are being developed and implemented in ocean models, with considerable uncertainty remaining on the relative importance of the processes which determine the final distribution of mixing. The role of interactions between internal waves and geostrophic flow in leading to mixing (Rainville and Pinkel, 2006; Dunphy and Lamb, 2013) remains poorly accounted for, and will require communication between internal-wave driven mixing parameterizations and representations of subgrid-scale mesoscale eddies.

The loss of energy from the internal wave field needs to be translated into a diffusivity, usually accomplished using a mixing efficiency argument (Osborn, 1980). Whereas, current climate models usually use a constant mixing efficiency, with some modifications for low stratification regions (Melet et al., 2013), a growing body of evidence suggests mixing efficiencies vary with process, and may depend on buoyancy Reynolds number (de Lavergne et al., 2016).

The final spatial distribution of interior diapycnal diffusivity ultimately depends on topography, tidal flow, latitude, changing stratification, and variable energy inputs from winds and geostrophic flow. Test simulations with different distributions of diapycnal diffusivity corresponding to the same net energy input indicate sensitivity of overturning circulation, thermocline stratification, and steric sea-level, to the vertical distribution of mixing in particular (Melet et al., 2016).

6.4. Submesoscale

Submesoscale processes are characterized by order one Rossby numbers, and thus sit at the boundary between the largely balanced mesoscale and the unbalanced gravity wave scales (McWilliams, 2016). The first submesoscale process to be parameterized for ocean circulation models was the restratification of upper ocean boundary layers by mixed layer eddies (Fox-Kemper et al., 2008; Fox-Kemper et al., 2011). This parameterization shoals the mixed layer, mostly in wintertime, and is in fairly wide use in ocean models. Observational analyses support the essential formulation of this parameterization (Johnson et al., 2016; du Plessis et al., 2017) and the associated biological impacts (Mahadevan et al., 2012; Omand et al., 2015). Other approaches have been proposed (e.g., Brüggemann and Eden, 2014). However, recent work has shown that when there is competition between boundary layer mixing or convection and submesoscales, the situation is more complex than presently parameterized (Haney, 2015; Smith et al., 2016; Whitt and Taylor, 2017; Callies and Ferrari, 2018). Furthermore, mesoscale fronts can strengthen or weaken the submesoscale restratification effects (Ramachandran et al., 2014; Stamper et al., 2018). Seasonality of these effects has been observed to be significant in some models and observations (Mensa et al., 2013; Callies et al., 2015; Rocha et al., 2016b), but not in the same way in other locations (Luo et al., 2016; MacKinnon et al., 2016; Viglione et al., 2018). It is not clear if these more complex scenarios can be robustly parameterized, but it remains useful to collect observations of a wide variety of submesoscale events to assess the basic and sophisticated versions seen in models.

A variety of other submesoscale processes are under study and awaiting parameterization development or vetting. A parameterization of symmetric mixed layer instabilities has been proposed for submesoscale-permitting models, but not carefully vetted in applications (Bachman et al., 2017b). Submesoscale effects in the oceanic bottom boundary layer are likely to have important consequences for drag and deep stratification (Wenegrat et al., 2018). Interactions between submesoscale and boundary layer turbulence are being simulated often in process studies, but they are not yet well understood (Hamlington et al., 2014; Haney, 2015; Smith et al., 2016; Whitt and Taylor, 2017; Callies and Ferrari, 2018).

6.5. Vertical Convection

As discussed above, the majority of ocean circulation models have assumed hydrostasy and shallow grid cells so that nonhydrostatic phenomena are not explictly resolved. Yet many oceanic phenomena have significant vertical velocities and convection, so these effects must be parameterized (Send and Marshall, 1995; Klinger et al., 1996). Surface boundary layer parameterizations incorporate convective mixing due to surface buoyancy loss (Mellor and Yamada, 1982; Large et al., 1994; Reichl and Hallberg, 2018). Prototype "superparameterizations" of these effects, involving 2-dimensional explicit simulations of convection within each horizontal grid-cell, are being studied (Campin et al., 2011). However, in the ocean interior, vertical convection driven by static instability is usually accounted for relatively crudely, through convective adjustment or via the Richardson-number dependent mixing scheme e.g., Jackson et al. (2008). A more physically-based parameterization of mixing due to convective overturns in the ocean interior, e.g., in breaking internal waves, Klymak and Legg (2010), has been implemented in regional and process simulations, but not in large-scale models. Convection due to subsurface input of fresh-water, e.g., from melting glaciers and ice-shelves, can be represented by buoyant plume models (Jenkins, 2011) which have been implemented into larger-scale GCMs (Slater et al., 2015).

6.6. Overflows

Dense water flowing from marginal seas and continental shelves into the deep ocean is an important source of abyssal and intermediate water. These overflows include many processes which occur below the grid scale, e.g., frictional boundary layer processes, entrainment of ambient water, hydraulic control at narrow straits and sills, which therefore must be parameterized (Legg et al., 2009). For coarse-resolution pressure-coordinate models, excessive numerical diffusion as dense water descends the slope is the most challenging issue (Winton et al., 1998); this can be reduced by numerical schemes such as Campin and Goosse (1999), Beckmann and Döscher (1997), and Bates et al. (2012a), as well as the NCAR overflow parameterization (WuG, 2007; Danabasoglu et al., 2010) which incorporates hydraulic control theory to prescribe the overflow transport and entrainment. Isopycnal coordinates suppress numerical diffusion (White et al., 2009; Ilicak et al., 2012), and when combined with suitable physical parameterizations of the mixing in the bottom boundary layer (Legg et al., 2006) and interfacial shear layer (Jackson et al., 2008), lead to improved Nordic overflows in climate model simulations (Wang et al., 2015). The representation of small-scale topographic control of overflows remains an outstanding issue, which may be solved by the use of partial-barriers and thin walls (Adcroft, 2013) for narrow channels, or enhancements to entrainment (Ilicak et al., 2011) for small-scale roughness.

6.7. Estuaries and Runoff

Freshwater input into ocean models has traditionally been very idealized, involving hand tuning of the region and depth range over which the runoff is introduced to produce a realistic plume. Sun et al. (2017) have implemented a estuary parameterization based on theory (Garvine and Whitney, 2006) that makes these treatments more realistic and less subjective. In the context of biogeochemical modeling, theories, observations and parameterizations for sources and sinks of biogeochemical tracers in estuaries and elsewhere are an important future direction.

7. MODEL DIAGNOSIS AND EVALUATION

7.1. Global Diagnostics

7.1.1. SST and SSS

SST contributes to the local air-sea heat flux and can regulate ocean-atmosphere coupling via SST-wind feedback. SSS does not directly affects the local air-sea heat flux, but it can influence SST and air-sea interactions indirectly where there is an SSS-induced barrier layer. A proper distribution of SST and SSS is needed, not only for air-sea interaction processes, but also to ensure a proper representation of water masses throughout the world ocean. SST is arguably the best known quantity because of high quality AVHRR satellite measurements since the 1980s and accurate *in situ* measurements for more than a century. Our knowledge of SSS is not as extensive as SST, mostly because satellite measurements of SSS are recent (SMOS in 2010, Aquarius in 2011, and SMAP in 2015) with coarse coverage (Lee and Gentemann, 2018).

In global ocean-ice models uncoupled from the atmosphere, the air-sea turbulent heat fluxes are derived from bulk formulae using a prescribed atmosphere which tend to damp SST differences from the air temperature and acts as a fluid with infinite heat capacity (Griffies et al., 2009). It also does not allow for any ocean feedback to the atmosphere. This feedback takes place via SST (Small et al., 2008) and ocean current/wind shear (Renault et al., 2016a). Interactions of ocean eddies and the atmosphere can regulate western boundary currents (Ma et al., 2016; Renault et al., 2016b). Furthermore, a bulk-forced oceanic uncoupled simulation should prescribe the surface stress using the relative wind using bulk formulae which take into account a parameterization of the partial re-energization of the ocean by the atmospheric response (Renault et al., 2016b).

Errors in SSS arise from inaccurate precipitation fields as well as from the modeled surface advection of the salinity fields. Contrary to the SST, there is no implied salinity restoring in the fresh water flux formulation to minimize the accumulation of flux errors and this will induce a drift in SSS in ocean-ice only simulations. Salinity restoring can minimize this drift, but it does not have any physical meaning (Griffies et al., 2009). The time scale associated with this restoring will also strongly impact the realism of the variability in surface salinity and associated water mass transformations. Furthermore, the SSS field to relax toward is subject to large uncertainties because SSS is still poorly observed when compared with SST, although improving through remote sensing of salinity (Boutin et al., 2018).

7.1.2. Ocean Heat Content

Box 3.1 in the IPCC AR5 report (Rhein et al., 2013) contains an iconic image indicating the predominant role of the ocean in determining the heat balance in the climate system. Largely supported by the advances in ocean temperature measurements made via Argo (Riser et al., 2016), we know that the ocean has absorbed more than 90% of the excess heat trapped in the climate system arising from anthropogenically produced greenhouse gases since 1970. If the ocean did not absorb this excess heat, then uniformly mixing that heat throughout the global atmosphere would warm it by roughly 40 K. This dominant role for the ocean in the earth's heat budget provides a mandate for the oceanography community to accurately represent and parameterize the multitude of processes that affect the transport of heat both laterally and vertically.

At the basin and planetary scales, poleward ocean heat transport is largely constrained by poleward atmospheric transport, which is itself constrained by differential heating between the equator and poles. In contrast, the patterns and rates of vertical heat transport between the ocean surface boundary layer and the ocean interior are largely determined by ocean processes, including small scale mixing induced by breaking gravity waves (MacKinnon et al., 2013, 2017), as well as mesoscale (Fox-Kemper et al., 2013) and submesoscale (McWilliams, 2016) currents, eddies, and filaments. These processes also constrain the meridional transport of salt in the ocean, with mesoscale eddies contributing as much as the time-mean circulation to the transport of salt out of the subtropical gyres (Treguier et al., 2014).

The connection between the planetary heat budget and ocean mixing and stirring has been known for decades, thus maintaining a rationale for conducting ocean research at climate centers. Advances made during the past decade in observations, processes modeling, and global climate modeling have enhanced the constraints on relevant ocean processes and their parameterizations. Even so, there remains significant work required to confidently constrain the rates and pathways for ocean heat uptake. One revealing example concerns the sensitivity of heat uptake to the representation and parameterization of ocean mesoscale eddies as found in a realistic climate model (Griffies et al., 2015b). It will be a decade or more before the $\mathcal{O}(4-10)$ km ocean grid spacing used in that study will become routinely available for climate centers, and even longer before the smaller submesoscale processes are routinely resolved.

7.1.3. Tracers

Much attention is paid to active tracers by ocean modelers, such as potential density and potential vorticity, because the distribution of these fields directly affect the circulation. However, many studies have shown that biogeochemical modeling is significantly hindered by the lack of attention paid to passive tracer dynamics (Doney et al., 2004), and anthropogenic ocean heat uptake tends to have marginal impacts on circulation and stratification, but is one of the three most important aspects of sea level rise (Palmer et al., 2018). Recent studies have shown that there is a distinction between Gent and McWilliams (1990) streamfunction and Redi (1982) diffusion coefficients (Smith and Marshall, 2009; Abernathey et al., 2013), but they are linked together in a nontrivial manner rather than totally unrelated (Dukowicz and Smith, 1997; Bachman and Fox-Kemper, 2013).

One method to allow for passive tracers to be mixed at a different rate from active tracers is horizontally anisotropic diffusion (Fox-Kemper et al., 2013) and a matched Gent and McWilliams (1990) operator (Smith and Gent, 2004). It has already been discussed that oceanic diffusion is anisotropic between the along-isopyncal and cross-isopycnal directions, but it is also anisotropic in the horizontal direction largely due to shear dispersion (Oh et al., 2000). If different tracers are assumed to have approximately the same anisotropic diffusivities and gauge, linear algebra methods have been developed to diagnose streamfunctions and diffusivities from multiple tracers at one time (Plumb and Mahlman, 1987; Bratseth, 1998; Bachman and Fox-Kemper, 2013; Bachman et al., 2015). These methods broadly support the Gent and McWilliams (1990) streamfunction and Redi (1982) diffusion operator forms, but they also allow for spatiotemporal examination of these fields and their relationships.

Other methods to allow for passive tracers to obey different behavior than active tracers include separating the Gent and McWilliams (1990) streamfunction and Redi (1982) diffusion or using different diffusivities or rotational gauges for different tracers (Eden, 2010). These methods suffer from underdetermination, however, as the anisotropic flux-gradient relationship for one tracer has more degrees of freedom than constraints, a situation that is made even more severe by freedom of gauge choice.

Observational diagnoses of diffusivities are becoming more common (Marshall et al., 2006; Abernathey and Marshall, 2013; Poje et al., 2014; Cole et al., 2015; Groeskamp et al., 2017), but different diagnostic techniques may result in different diffusivities (Klocker et al., 2012; Pearson et al., 2018). Synthetic "observations" created in a model simulation are recommended for evaluation on an equal basis to the observations. Furthermore, anisotropic diffusion is typically neglected in these diagnostics (Fox-Kemper et al., 2013).

7.1.4. Sea Level

Sea level rise is among the most prominent of societal impacts from anthropogenic climate warming, affecting millions of people who live near coasts and many more affected by migrations away from coasts. Ocean warming has contributed to roughly one-third to one-half of the observed global mean sea level rise during recent decades, with added mass from melting land ice contributing the remainder. Ocean and climate models are the primary tool used to quantify how ocean heating contributes to sea level changes at both global (e.g., Gregory et al., 2013) and regional (e.g., Griffies et al., 2014) scales.

The ocean thermal expansion coefficient is a strong function of temperature, reducing an order of magnitude between the warm tropics and the cold high latitudes (e.g., see Figure 1 of Griffies et al., 2014). Consequently, a unit of heat added to the low latitudes impacts on sea level rise more than the equivalent heat added to the high latitude oceans. Furthermore, ocean circulation moves heat throughout the ocean, thus contributing to regional patterns of thermosteric sea level change. Consequently, the accurate projection of global and regional sea level changes involves more than just how much heat crosses the ocean surface. Salinity changes also contribute to regional patterns of halosteric sea level. Indeed, in the Atlantic a negative halosteric sea level change, due to regional increases in salinity, acts to compensate regional thermosteric rise due to warming (e.g., see Yin et al., 2010). Even so, global halosteric sea level changes are negligible since the mass impact on sea level from changes to freshwater content dominate the corresponding changes to halosteric sea level (Lowe and Gregory, 2006).

Ocean and climate models provide a tool to quantify how physical processes impact both regional and global sea level patterns. Griffies and Greatbatch (2012) formulated methods to decompose the global mean sea level budget into physical processes, whereas Gregory et al. (2016) detail an experimental protocol to quantify how changes in heat fluxes, water fluxes, and wind stresses impact on regional sea level patterns (the CMIP6 Flux Anomaly Forced MIP, FAFMIP). These approaches provide frameworks for comparing and contrasting the variety of model projections of sea level, and thus for use in identifying, at a process level, sources for model uncertainties that commonly plague simulations of sea level change particularly at the regional scale.

7.1.5. Ocean Mass and Angular Momentum

The three primary components of global sea level rise are ocean thermosteric expansion, glacier melt and changes in land storage of water, and melting ice sheets. Only the first does not imply a change in the mass of the oceans. Satellites such as the Gravity Recovery and Climate Experiment (GRACE) can directly measure changes in the mass of the oceans through their effects on the earth's gravitational field. Traditional Boussinesq ocean models with a rigid lid struggled to incorporate such changes in mass through freshwater input, because they were models with a fixed volume of fluid so any changes in mass had to come through virtual salt fluxes or temperature-related density changes.

However, modern models using an explicit free surface with a natural water boundary condition overcome the limitations of the rigid lid (e.g., Griffies et al., 2001; Campin et al., 2004), thus accepting changes in ocean volume even while preserving Boussinesq dynamics. This numerical improvement, or post-simulation analysis with similar intent (Griffies and Greatbatch, 2012), has greatly improved the directness of sea level change estimation within the model framework. When coupled with active ice sheet models, ocean models are beginning to directly simulate the needed components of sea level change.

In situ observations of ocean bottom pressure, i.e., the weight per unit area of the ocean above (Hughes et al., 2018), GRACE measurements (Watkins et al., 2015; Save et al., 2016), and data assimilating models spanning annual to decadal time scales (Ponte et al., 2007; Stammer et al., 2010; Köhl et al., 2012; Johnson and Chambers, 2013) are important aspects of continuing to improve ocean models' capability to simulate all important aspects of climate. Tides (Arbic et al., 2018) and forcing of other high-frequency waves (Callies and Ferrari, 2013) are an important new aspect of high-resolution (mesoscale and submesoscale-permitting) simulations, especially in data assimilating and Lagrangian transport contexts where it has proven very difficult to find effective ways to completely filter these motions from observations (e.g., Beron-Vera and LaCasce, 2016; Buijsman et al., 2017). Gravitational self attraction and loading (i.e., the elastic response of the lithosphere to changes in ocean mass) is now well-known to be important in tide simulations, but their impact on ocean circulation and ocean circulation sensitivity is only recently being considered (Kopp et al., 2010; Slangen et al., 2014; Vinogradova et al., 2015; Arbic et al., 2018). It is through comparison of ocean circulation models, bottom pressure records, and gravity recovery missions that these physical relationships will become understood and effectively simulated.

Finally, ocean angular momentum diagnostics (along with those of the atmosphere) provide valuable information on Earth rotation variability and its relation to oceanic mass transport (Ponte et al., 2001). Calculating long-term trends in ocean angular momentum and implied changes in length-of-day estimates benefits substantially from models that have been rigorously constrained by observations through state and parameter estimation (Quinn et al., 2018).

7.1.6. Meridional Transport

Meridional transport of freshwater and heat is a traditional diagnostic of models, both in mean overturning and eddying components. The advent of continuous monitoring of the RAPID/MOCHA, OSNAP, and SAMOC mooring arrays provides a new tool for model evaluation. The first, RAPID/MOCHA array resulted in significant improvement of models to come into agreement (Msadek et al., 2013). Griffies et al. (2016) present in their table J2 the most important mass transport sections that should be evaluated in models, with recent observation estimates (e.g., Drake Passage transport recently revised to a 30% higher value by Donohue et al., 2016).

7.2. Process Diagnostics

7.2.1. Eulerian

While Eulerian observations and diagnostics are as old as oceanography itself, recent work combining mooring time series for a frequency spectrum evaluation of high resolution ocean and tide models is notable (Arbic et al., 2018).

7.2.2. Lagrangian

Lagrangian particle tracking methods can be used to map ocean circulation pathways determined by the ocean velocity field (e.g., Tamsitt et al., 2017; Lique and Thomas, 2018; van Sebille et al., 2018). Additionally, such methods can be used to objectively quantify how much transport arises from coherent ocean vortices (e.g., see Haller, 2015; Abernathey and Haller, 2018; Tarshish et al., 2018 and references therein). So long as sufficient velocity data is available to compute the particle trajectories, and sampling biases are managed (Pearson et al., 2017), Lagrangian analysis methods offer a powerful tool to diagnostically probe properties of the circulation, including its turbulent properties. These methods, however, are limited in their ability to deduce pathways for tracer transport given that

Lagrangian particle pathways are generally computed without the direct impact from mixing, whereas mixing can be important for determining tracer pathways and timescales.

7.2.3. Turbulence

As more sophisticated models of turbulent mixing are developed, the veracity of these parameterizations can be evaluated by comparing the 3D spatial patterns of diffusivity or dissipation generated by these models and their temporal variations with observations (Whalen et al., 2012, 2018; Sutherland et al., 2013; Waterhouse et al., 2014; Kunze, 2017). Parameterizations of turbulent mixing can also be evaluated by examining their impact on the simulated ocean circulation and climate. A series of investigations using the GFDL-ESM2G coupled climate model explore the impact of different components of internal wave driven mixing, including the vertical structure of the local dissipation of the internal tide (Melet et al., 2013), the inclusion of breaking lee-waves due to geostrophic flow over topography (Melet et al., 2014), and different choices for the farfield component of internal tide breaking (Melet et al., 2016). These studies indicate that both the total energy used for mixing and its spatial distribution matters to the circulation. The vertical distribution of mixing is particularly important: more mixing in the deep ocean results in stronger, deeper overturning, while more mixing in the upper ocean leads to stronger shallow subtropical overturning cells and a more diffuse thermocline (Melet et al., 2013, 2016). The horizontal distribution of mixing is particularly important when the sources of deep water masses are differentially affected, for example by lee-wave driven mixing in the deep Southern Ocean (Melet et al., 2014), or by mixing on high latitude shelves and slopes (Melet et al., 2016). Ocean-only MITgcm simulations by Eden et al. (2014) have explored the impact of the energetically-consistent internal wave and mesoscale eddy-driven mixing, and similarly find that enhanced mixing at depth drives a stronger overturning circulation.

7.2.4. Submesoscale

The submesoscale is challenging to evaluate diagnostically in comparison to observations, as the features are small (km) and evolve rapidly (hours). However, recent projects have provided observations that are capable of evaluating and constraining submesoscale model behavior through models initialized alongside observations (Mahadevan et al., 2012; Omand et al., 2015), scaling relations (Johnson et al., 2016; du Plessis et al., 2017), and intensive observations (Shcherbina et al., 2013; Poje et al., 2014).

7.2.5. Water Masses

As recently reviewed by Groeskamp et al. (2019), the water mass transformation (WMT) framework weaves together circulation, thermodynamics, and biogeochemistry into a description of the ocean that complements Eulerian and Lagrangian methods. In so doing, a WMT analysis offers novel insights and predictive capabilities for studies of ocean physics and biogeochemistry. A WMT analysis is layer-based, thus aiming to remain faithful to the layered structure of the ocean thermodynamic and tracer properties. Since the pioneering work of Walin (1982), there have been numerous studies using both observational and model datasets, aiming to understand and quantify water mass properties and their transformations. Many studies provide inferential estimates of transformations based on surface properties and boundary fluxes (e.g., Large and Nurser, 2001). The incorporation of biogeochemical tracers into the WMT framework remains a cutting-edge use of the analysis method (Iudicone et al., 2011).

Models offer the ability to move beyond the traditional inferential methods commonly employed with WMT analysis. Doing so requires the development of online binned budget diagnostics so that tendencies from all processes within the ocean can be explicitly determined. As a result, the analysis will allow for an accurate deductive rendition of the transformation processes ongoing within the model, and how these processes affect simulated water mass properties.

7.2.6. Energetics

A powerful diagnostic tool used since Lorenz (1955) is the evaluation of energy reservoirs and transfers. This approach can be used to evaluate mesoscale eddy parameterizations, as they frequently rely on extraction rate of potential energy (Gent and McWilliams, 1990) or the reservoir of kinetic energy (Marshall et al., 2017). Global estimates of the energy available for diapycnal mixing from the tide and wind (Ferrari and Wunsch, 2009) are a valuable diagnostic for evaluation of mixing parameterizations (MacKinnon et al., 2017). In some circumstances, the class of turbulent instabilities can be recognized using energetics when other aspects of the structures are not recognizable (Haney et al., 2015).

7.2.7. Vorticity

Vorticity budgets are another powerful tool in diagnosing the mechanisms underlying the control of the oceanic general circulation (Fox-Kemper and Pedlosky, 2004; Yeager, 2015). Unlike the energy budget, which can be complicated by non-local radiation effects (Plumb, 1983), the vorticity budget is closed locally (although it can be difficult to assess the cause of vertical stretching terms). Enstrophy or potential enstrophy are useful diagnostics of 2D and quasigeostrophic turbulence (Fox-Kemper and Menemenlis, 2008; Bachman et al., 2017a; Pearson et al., 2017; Pearson and Fox-Kemper, 2018).

Vorticity diagnostics applied to global models of full complexity have revealed the importance of bottom vortex stretching in the balance of western boundary currents (Hughes and de Cuevas, 2001), the Atlantic northern recirculation gyre (Zhang and Vallis, 2007), North Atlantic Deep Water pathways (Spence et al., 2012), and the Atlantic subpolar gyre and meridional overturning circulations (Yeager, 2015). The Argo array of float measurements to 2,000 db has permitted global tests of linear vorticity theory (Gray and Riser, 2014), but deeper measurements are needed to validate model results showing ubiquitous and large deep transports balanced by topographic stretching (Thomas et al., 2014). In eddy-resolving simulations, vorticity analysis highlights the role of mean nonlinear advection and eddy momentum flux in a variety of contexts (Delman et al., 2015; Wang et al., 2017; Wang H. et al., 2018).

8. NOVEL APPLICATIONS

8.1. Southern Ocean

The Southern Ocean is a major sink for anthropogenic energy and carbon, due to the competition of the Ekman and eddy overturning circulations of the SOMOC and the formation of Antarctic Bottom Water. This complex set of phenomena has significantly challenged model capabilities, leading to a variety of model resolution hierarchy studies (Hallberg and Gnanadesikan, 2006; Ito and Marshall, 2008; Munday et al., 2013; Bryan et al., 2014; Marshall et al., 2017). One analysis of a fully-coupled atmosphere-ice-ocean simulation at mesoscale-resolving resolution yielded eddy saturation effects in a natural manner (Bishop et al., 2016).

The DIMES (Sheen et al., 2013), SMILES (Adams et al., 2017), and SOCCOM (Russell et al., 2014) experiments all have matching modeling exercises to explore the impacts of mixing, submesoscales, and processes affecting biogeochemistry of the Southern Ocean. Matched or idealized simulations have led to better understanding of the context of the observations and dynamical insights (Bates et al., 2014; Bachman et al., 2017c; Bronselaer et al., 2017; Stamper et al., 2018).

8.2. Arctic

Progress in modeling the Arctic ocean has occurred through improved sea ice models as well as higher horizontal and vertical resolution, which allow a better representation of currents through the Canadian Archipelago (Hughes et al., 2017) and a better representation of the complex stratification of Arctic watermasses (Wang Q. et al., 2018). New *in situ* and satellite observations are used to evalutate operational models (Dupont et al., 2015) and reveal processes that are being investigated with models, such as the seasonal cycle in the Atlantic waters (Lique and Steele, 2012). With the decline of summer sea ice and the increased Greenland runoff through fjords, the Arctic freshwater balance is an evolving challenge for models (Lique et al., 2015).

8.3. Atlantic Meridional Overturning Circulation

Through its associated heat and salt transports, the Atlantic meridional overturning circulation (AMOC) significantly influences not only the climate of the North Atlantic and surrounding areas, but also the climate of the entire globe via oceanic and atmospheric teleconnections. In particular, changes in sea surface temperatures (SSTs) linked to AMOC variability can impact climate on interannual to (multi)decadal to even longer time scales, thus making AMOC a central piece of prediction efforts of the earth's future climate on these time scales. Essentially, AMOC is thought to contain the dynamical memory of the climate system.

The representation of AMOC mean and variability continues to exhibit significant differences among fully-coupled, pre-industrial control simulations of the earth system models, e.g., those participating in the Coupled Model Intercomparison Project phase 5 (CMIP5). In addition to important differences in peak periods and amplitudes of intrinsic variability among them, several aspects of proposed natural variability mechanisms also differ. The roles and impacts of external forcings vs. internal variability in driving variability in AMOC and related, climatically important fields, such as SSTs, during the historical period also remain largely unresolved.

The representation of AMOC mean similarly differs among ocean sea-ice coupled hindcast simulations that were performed as part of the CORE-II ocean model intercomparison effort, despite using the same atmospheric forcing datasets (Danabasoglu et al., 2014). Such differences do not necessarily suggest an obvious grouping of the ocean models based on their lineage, their vertical coordinate representations, or surface salinity restoring strengths. The differences can be partially attributed to use of different subgrid scale parameterizations and parameter choices, to differences in vertical and horizontal grid resolutions in their ocean models, as well as to use of diverse snow and sea-ice albedo treatments. These hindcast simulations, however, tend to show general agreement in their temporal representations of AMOC and SST variabilities, e.g., the observed variability of the North Atlantic SSTs is captured well by the models (Danabasoglu et al., 2016). This suggests that the simulated variability and trends are primarily dictated by the forcings which already include the influence of ocean dynamics from nature superimposed onto external and anthropogenic effects. Nevertheless, there are many important differences among the model solutions, including the spatial structures of variability patterns and where the maximum AMOC variability occurs.

The representation of AMOC mean and variability is also as diverse among various reanalysis products (Karspeck et al., 2016). Arguably, the reanalysis products appear to be less consistent with each other in their AMOC means and its interannual to decadal variability than those of forced hindcast simulations participating in the CORE-II effort.

To resolve these differences in models representations of AMOC mean and variability, including the driving mechanisms, requires basin-wide continuous and comprehensive observations. In particular, identification of robust variability mechanisms has important implications for climate (decadal) prediction efforts both to shed light on sources of skill and subsequently use that knowledge to improve skill. The importance of such trans-basin observational systems has been recognized and several efforts have been in place, starting in 2004. A summary of these observational programs along with recommendations for future observations is provided in Frajka-Williams et al. (2018). A recent review of the AMOC that includes its mean spatial structure, temporal variability, and proposed driving mechanisms is provided by Buckley and Marshall (2016).

8.4. Sea Level Change

As societal impacts respond to relative sea level change, not global mean sea level change, the oceanic and geophysical aspects of the regional sea level problem have been studied heavily in the last decade. One ocean modeling tool that has proven useful is the use of an ocean state estimate (Forget and Ponte, 2015; Stammer et al., 2016) or reanalysis to provide insight into the patterns of regional sea level rise (Vinogradov et al., 2008; Piecuch and Ponte, 2014; Calafat et al., 2018). Future work in this direction will aid in prediction of ocean dynamics effects on sea level.

8.5. Global Coupled Mesoscale-Permitting

Global ocean-only and ocean-ice forced high resolution simulations have been possible for a few decades (Semtner and Chervin, 1992; Maltrud and McClean, 2005; Chassignet et al., 2009). However, recently *coupled* simulations have brought climate modeling capabilities into the mesoscale-resolving or mesoscale-permitting regime (McClean et al., 2011; Small et al., 2014; Griffies et al., 2015b; Hewitt et al., 2016). While all aspects of resolving mesoscale features are not yet discovered, it is already clear that air-sea fluxes are fundamentally affected (Bishop et al., 2017) and that dampening of oceanic variability through coupling with the atmosphere is one prominent effect (Ma et al., 2016; Renault et al., 2018). At present, most of these efforts use relatively simple subgrid dissipation schemes and parameterizations of unresolved smaller mesoscale and submesoscale eddies, but a few parameterizations have been proposed for this regime (Bachman et al., 2017b; Zanna et al., 2017) and one has been tested with promising results (Pearson et al., 2017). Interestingly, the lower horizontal dissipation in these simulations makes bottom drag more important energetically (Pearson et al., 2017), which makes returning to a careful consideration of the amount of bottom drag used more important (Sen et al., 2008; Arbic et al., 2009).

8.6. Global Submesoscale-Permitting

Taking advantage of improvements in numerics, computing, and scale-aware parameterizations, a heroic calculation of an ocean-ice configuration MITgcm at nominal 2 km global resolution has been run for 2 years of simulated time including all realistic forcing, including tides. These simulations allow for large region and global assessment of large submesoscale phenomena and tide-current coupling (Rocha et al., 2016a,b; Su et al., 2018), building on earlier work on tides in HYCOM (Shriver et al., 2014).

8.7. Ocean State Estimates and Reanalyses

Numerous advances have been made in ocean state estimation methods. For many quantities, ocean reanalyses have reached a degree of accuracy at which they could be considered in IPCC evaluations (Carton et al., 2018). However, significant model disagreement remains in some features such as the AMOC (Karspeck et al., 2016). Ensemble methods have also become more effective as resolution has increased, permitting fronts and eddies (Penny et al., 2015; Penny, 2017). The first modern-era coupled reanalysis of the global atmosphere, ocean, land surface, and cryosphere was created by NCEP with the Climate Forecast System Reanalysis spanning the period 1979 onward (CFSR; Saha et al., 2010). More recently, ECMWF generated a longer coupled reanalysis spanning the twentieth century (Laloyaux et al., 2018). Large biases have been identified in atmospheric-only surface forcing data sets (Tsujino et al., 2018) and it is expected that coupled reanalyses will become the standard to resolve these issues. An important distinction in methods is that between filter vs. smoother approaches. The former is the method of choice in the context of prediction, whereas the latter has been used for reconstruction (e.g., Wunsch and Heimbach, 2013; Stammer et al., 2016).

8.8. Decadal Prediction

The possibility of using coupled climate models for forecasting on decadal timescales was first explored in several perfect model and potential predictability studies (Griffies and Bryan, 1997; Boer, 2004; Pohlmann et al., 2004; Collins et al., 2006) and was soon thereafter tested using ensembles initialized from observation-based reconstructions (Smith et al., 2007; Keenlyside et al., 2008; Pohlmann et al., 2009; Yeager et al., 2012; Meehl et al., 2014; Scaife et al., 2014). The North Atlantic is a region consistently found to exhibit prediction skill on decadal timescales associated with ocean thermohaline circulation memory (Yeager and Robson, 2017), with predictable Atlantic sea surface temperature underpinning skill in seasonal climate over land regions such as the African Sahel (Yeager et al., 2018). With an accurate initialization of the coupled system, particularly the ocean state as determined from monitoring systems, then useful prediction of some aspects of regional climate 10 years in advance appears to be a realizable goal. Hypothetically, mesoscale-resolving ocean models will provide even better prediction system skill and predictability, through improved mesoscale air-sea interaction and reduced ocean bias (Siqueira and Kirtman, 2016). However, mesoscale eddy dynamics generate interannual large scale variability (Penduff et al., 2011) with low predictability, which has been addressed with a large ensemble approach (Leroux et al., 2018). To use mesoscale-resolving models in a forecast system, advanced data assimilation techniques, such as the ensemble Kalman filter, are needed to manage the large volumes of data involved.

9. WHAT TO EXPECT BY 2030

Ocean modeling continues to improve. Over the next decade, we expect:

- Resolution approximately a factor of 2 finer: 0.5° to 0.1° models will be common and global 1 km models in prototype evaluation. However, the rate of resolution refinement in ocean models has decreased by about 10% after 30 years of steady improvements. This may represent a reduction in resources, a failure in Moore's law, or a shift toward more complex models or large ensembles.
- Continuing improvement and familiarity using unstructured grids and ALE vertical coordinates.
- Nested and regional downscaling simulations connecting coastal impacts–inundation, ice shelves, sea level–and global changes.
- Increased use of ensembles of high-resolution ocean models and coupled models, which help to distinguish internal variability from forced and climate from weather.
- New parameterizations and improvements of existing parameterizations: Stochastic parameterizations are being explored for eddies (Grooms and Majda, 2013; Grooms, 2016), mixing (Juricke et al., 2017), air-sea fluxes (Williams,

2012), and parameterizations generally (Brankart, 2013; Andrejczuk et al., 2016); energetically-consistent schemes are under development (Eden et al., 2014; MacKinnon et al., 2017; Marshall et al., 2017); submesoscale (Fox-Kemper et al., 2011) and Langmuir (Li et al., 2017) turbulence parameterizations are becoming common; sensitivity to surface wave effects on mixing (Qiao et al., 2016) and air-sea fluxes (Zhao et al., 2017) are being explored; generation of gravity waves over bottom topography (Trossman et al., 2013, 2016); vertical convection is improving (Klymak and Legg, 2010; Campin et al., 2011); and coastal estuaries (Sun et al., 2017) have been parameterized over the last decade. Competition and complementary parameterizations will arise approximating other aspects of these unresolved phenomena.
- Improvements to air-sea and air-ice coupling, through numerical improvements, resolution, tighter coupling between ocean and ice dynamics, and a better representation of the impacts of surface waves.
- More direct simulation of sea level change, through oceanic free surface permitting numerics, actively simulated ice sheets and ice shelves, and improved and efficient incorporation of geophysical aspects of oceanic change such as self-attraction and loading.
- More direct simulation of tides, especially in high-resolution models, following recent progress in HYCOM and the MITgcm (Shriver et al., 2014; Rocha et al., 2016a,b; Ansong et al., 2017; Buijsman et al., 2017; Arbic et al., 2018; Su et al., 2018).
- More quantitative paleoclimate constraints on ocean circulation and change. Proxy modeling is one important step in this direction (Dee et al., 2015), as are simulated proxies (Stevenson et al., 2018). Until recently proxies for some ocean variables have been too uncertain or sparse to quantitatively constrain models (Stevenson et al., 2013; Amrhein et al., 2018; Bereiter et al., 2018), although sea level is an important exception (e.g., Miller et al., 2013).
- Increasing use of artificial intelligence, neural networks, and deep learning as part of the development and improvement of parameterizations–particularly in their numerical optimization for efficiency (Schneider et al., 2017; Gentine et al., 2018; Bolton and Zanna, 2019). These efforts may lead to reduced use of FORTRAN in favor of more modern computing languages such as Python and Julia (e.g., Häfner et al., 2018).

Sea ice modeling is expected to improve through (Notz and Bitz, 2016; Smith et al., 2018):

- Ice floe size prediction with ice–wave interactions.
- Anisotropy and lead orientation prediction.
- Realistic treatment of snow, melt ponds, evolution of salinity, and light-absorbing particles.
- Grid refinement in regions where small scale processes are needed to be resolved.
- Consistent models of sea-ice rheology and microstructure evolution based on first physical principles.

Key observational constraints for the next decade that would be useful in the above lists are:

- Analysis of high-resolution observations using scale-selective diagnostics of ocean tracer and momentum covariances, such as spectra, cospectra, structure functions, and relative dispersion. These analyses are key for constraining high-resolution models, which may share many of the same biases as coarse resolution models, but also are expected to have new biases related to improper small-scale phenomena. The development of subgrid schemes for high-resolution models requires observations that can distinguish good high-resolution models from bad.
- The follow-on mission to GRACE, GRACE-FO, will continue the improvements in modeling ocean and ice mass relocation, as well as other important aspects of the satellite constellation for ocean observation and monitoring. The proposed satellites capable of simultaneously constraining wind, wave, and currents such as SKIM, will be highly valuable in evaluating the formulation of high-resolution the coupled wave-ocean-sea ice simulations. SST, ocean color, and altimetry remain crucial in both data assimilation and model evaluation.
- Continued long-term and deep monitoring of the slow changes to the earth system, many of which are oceanographic. Our history of high quality observations is only slightly longer than a century (Roemmich et al., 2012), but it is well-known that ocean model statistics take 2–20 times longer to manifest (Wittenberg, 2009; Stevenson et al., 2010; Lindsay, 2017). Paleoclimate evidence provides reason to worry about the accuracy of low-frequency model variability (Laepple and Huybers, 2014).
- Increased observations in the polar regions, which challenge both ocean and cryospheric models. Under ice shelf and repeat sampling of evolving sea ice conditions are particularly essential to optimizing the coupled models discussed here.
- Continued progress on continously-uploaded monitoring systems, such as GOOS, that can be used in ocean state estimates, decadal forecasts, and forcing products.
- Increased observations in the deep ocean, particularly near topography, will be vital for constraining slow changes to the ocean reservoirs, key turbulent mixing, and boundary-confined flows. Deep Argo floats may be one component of this measuring system; others include more routine and possibly automated microstructure measurements as well as new capabilities for measuring turbulent quantities in the bottom boundary layer.
- The use of ocean state and parameter estimation to provide a comprehensive framework for formal model calibration.
- The use of observing system simulation experiments and optimal observing network design approaches in the context of ocean state and parameter estimation to predict the result of instrument deployments to result in better targeting of key areas and instrument accuracy requirements.
- The use of ocean state estimates to provide a context for observations.

- The continued successful partnerships between global modelers, process modelers and observationalists to drive process understanding and innovation in observing and parameterizations.
- Simulations of ensembles of observations similar to those that were collected to estimate bias and systematic errors.

9.1. Did the OceanObs09 "What to Expect?" Correctly Predict?

Griffies et al. (2010) state that "The origins of these biases and model differences may be related to shortcomings in grid resolution; improper numerical algorithms; incorrect or missing subgrid scale parameterizations; improper representation of other climate components such as the atmosphere, cryosphere, and biogeochemistry; all of the above, or something else." It is clear from this review that progress has indeed been made on all of these fronts in the last decade. They also proposed that deep insight would be learned from the study of AMOC variability and stability, patterns of sea level rise, and the Southern Ocean. Indeed, the simulations and analyses featured above focused on these aspects of the earth system have revealed important new insights, but also new challenges and prospects.

AUTHOR CONTRIBUTIONS

BF-K with significant input from SL, SG, and SJM, created the outline of topics and wrote the proposal. The authors of Griffies et al. (2010) and the CLIVAR Ocean Model Development Panel members were asked to contribute or recommend other authors. All authors then contributed to the writing and editing process and recommended references and examples.

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Ocean Data Product Integration Through Innovation-The Next Level of Data Interoperability

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In the next decade the pressures on ocean systems and the communities that rely on them will increase along with impacts from the multiple stressors of climate change and human activities. Our ability to manage and sustain our oceans will depend on the data we collect and the information and knowledge derived from it. Much of the uptake of this knowledge will be outside the ocean domain, for example by policy makers, local Governments, custodians, and other organizations, so it is imperative that we democratize or open the access and use of ocean data. This paper looks at how technologies, scoped by standards, best practice and communities of practice, can be deployed to change the way that ocean data is accessed, utilized, augmented and transformed into information and knowledge. The current portal-download model which requires the user to know what data exists, where it is stored, in what format and with what processing, limits the uptake and use of ocean data. Using examples from a range of disciplines, a web services model of data and information flows is presented. A framework is described, including the systems, processes and human components, which delivers a radical rethink about the delivery of knowledge from ocean data. A series of statements describe parts of the future vision along with recommendations about how this may be achieved. The paper recommends the development of virtual test-beds for end-to-end development of new data workflows and knowledge pathways. This supports the continued development, rationalization and uptake of standards, creates a platform around which a community of practice can be developed, promotes cross discipline engagement from ocean science through to ocean policy, allows for the commercial sector, including the informatics sector, to partner in delivering outcomes and provides a focus to leverage long term sustained funding. The next 10 years will be "make or break" for many ocean systems. The decadal challenge is to develop the governance and co-operative mechanisms to harness emerging information technology to deliver on the goal of generating the information and knowledge required to sustain oceans into the future.

Keywords: data standards, data democratization, end user engagement, data innovation, data integrity

INTRODUCTION

The Earth's surface is 70% ocean, with 40% of humanity living within 100 kilometers of the sea and an even larger proportion reliant on ocean ecosystem services (UN, 2017). Despite its central value to the lives of so many, fundamental information about how our oceans work is only available to a small community of scientists and operational experts. Rapid developments in sensor technologies are providing greater volumes of valuable data than ever before, thus there is a pronounced need for innovation in providing access to a wider collection of stakeholders.

Improving global understanding of our oceans and their value will rely on innovation that removes barriers between each group of users (including potential users) and the marine data most relevant to their needs. This will require new information and data pathways which open up, adaptively structure, and explain complex ocean data to anyone who can generate value and knowledge from it. Simultaneously, improving the connectivity between data networks and facilitating the integration of new sensors will rapidly improve monitoring activities such as maritime safety (piloting and dredging), the prediction of ocean hazards such as Tsunamis, and the disentangling of natural variably from human-induced impact in the natural environment.

While the possibilities are immense, sizeable obstacles currently impede global, interdisciplinary, and inclusive progress. For example, the majority of oceanographic data available today are downloadable from web portals which have tailored their search interfaces and data products to highly specialized consumers, limiting generalized use and cross-boundary innovation. Data are also often available from disparate networks, in a variety of formats and with sparse or poorly structured metadata. Collectively, these issues greatly slow the discovery and use of ocean data, as well as the generation of downstream products and knowledge.

This paper examines the frameworks, standards, protocols and pathways required to break free of the current "portal and download" model of data access and move to a system based on interoperable services, allowing users to configure and apply varied yet compatible ocean data services to build their own knowledge systems. In particular, we explore solutions which will allow new data flows around models, artificial intelligence, and user-defined knowledge systems.

Under the banner of the "democratization of data," a series of examples from other disciplines are dissected to look at what the framework needs to deliver and how this democratization is currently being done in other areas. The need to ensure that data provenance, Quality Control (QC) information, appropriate use and attribution information are embedded in any data access workflow is fundamental to ensuring user trust in the data and any products generated and so the paper focuses on issues of cyber-security and provenance. The standards, protocols, technologies, and tools that link the various parts of the workflow into a true framework are also detailed along with a number of Use-Cases that demonstrate the current state of the art in ocean data systems. Finally, the vision of what this open access to data may look like and how it may work are presented along with a set of recommendations for advancing this over the next decade, or sooner.

To provide context, a Data Life Cycle diagram is shown (**Figure 1**), which visualizes the various stages in data workflows from sensor to user, the roles and organizations involved and what structural units are required to deliver the workflow. **Figure 2** is a schematic of what a future work-flow may look like with the concepts of information and knowledge brokers introduced as key parts of the work-flow. Finally, **Figure 3** shows how data integrity is delivered by the work-flow, particularly from sensor to data center, and how this may be secured.

The coming decade will see rapid advances in our ability to collect data, the challenge is to develop the frameworks and work flows to similarly increase the conversion of data to information, to facilitate and encourage the uptake and use of the data, and to ensure that the decisions that impact the state of the oceans in 10 years are based on creditable, defensible, understood data generated from high quality sustained observations.

DEMOCRATIZATION OF DATA

The democratization of data is the process of making data that is difficult or complex to find, understand and use, available to anyone in a way that makes sense to them. Given that most ocean data are funded by various national and international government programs, there is an expectation that publicly funded data should be freely and easily available to the public: data paid for by the people for use by the people. For most ocean data this is currently not the case. The idea behind data democratization is to change this.

While there have been efforts to make ocean data freely available, via portals and other mechanisms, there are still substantial barriers to entry for people outside the ocean community. Even within the ocean community barriers exist; for example, most biologists struggle to use file formats such as NetCDF. For simple data sets, such as satellite-derived Sea

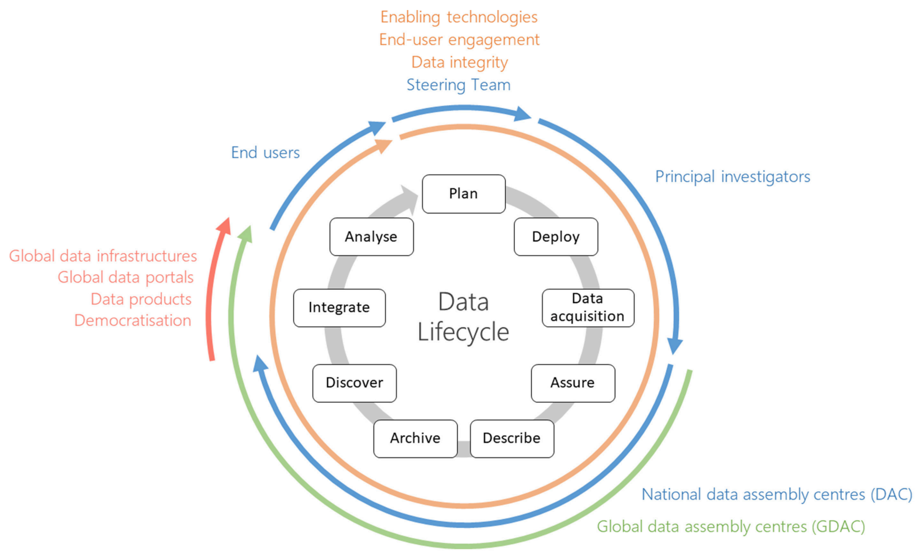

FIGURE 1 | Roles and processes involved in the data lifecycle.

Surface Temperature[1], there are numerous sites with varying products, making it difficult for non-experts to understand. If ocean data is to impact how we use, manage and sustain our oceans then it needs to be available in a form that provides value and satisfies the needs of end users from all communities. This democratization of data requires a new paradigm for how data is converted into information, and ultimately knowledge, which leverages new information frameworks and rethinks how people use and gain value from data.

An example from the marine community where effort toward democratization of data has begun is the MedSea project[2] (Ziveri, 2014). The EMODnet Med Sea checkpoint[3] is a Mediterranean Sea wide monitoring system and assessment activity based upon targeted end-user applications including windfarm siting, managing marine protected areas, detecting oil platform leakage, climate and coastal protection, fisheries management, marine environmental management, and monitoring river inputs to the coastal environment. The goal was to provide a basis for rational decision-making, assessing the status of the Mediterranean Sea observing and modeling infrastructure, analyzing gaps, and identifying priorities to optimize regional monitoring and sampling strategies. Examples of applications of this work are oil spill management and safer professional and recreational activities (Liubartseva et al., 2016; Coppini et al., 2017). Other related but less mature EMODnet activities for different regions that are illustrative of European policy are for the Atlantic as part of the AtlantOS project (Koop-Jakobsen et al., 2016) and North Sea Checkpoint project[4].

The new paradigm looks to reverse how ocean data is traditionally accessed and used. In this paradigm the user defines the way the information derived from data is converted to knowledge. The end users are empowered to create knowledge relevant to their own needs from the data and information provided. This is the reverse of traditional systems where the custodian of the data pre-defines the use and constraints of the data and in so doing defines the knowledge that can be extracted. The knowledge a shipping company extracts from current data may be very different to that a marine insurance company, local sailor, or fisherman derives.

The new paradigm is built around Data as a Service (DaaS), where data sets are made available as fully-described, web-enabled data streams. This removes the need to download data from a portal or data store, to know what data exists and where it resides, to be able to understand and decode the storage format and to manually convert it to a form that adds value to the end user (such as changing units, datum, etc.). The DaaS concept enables machine systems to discover, access and deliver data, providing an underlying set of services on which information systems can be built (Terzo et al., 2013).

So how would this work and what would it look like? Four examples are given, showing a range of models from currently existing systems, including how the data is arranged and sourced, how the system adds value, and how it is supported by an underlying business model.

Google Scholar[5] provides a single interface for finding and accessing scientific literature as well as tools for citing publications. The system uses "GoogleBots" or web "crawlers" to extract information from publishers' web sites and collate it into a form suitable for public access and use. The data source is therefore un-federated (no single source of data) and the extraction is passive from the point of the data custodian. The system adds value by providing a single point of access to the

[1]https://podaac.jpl.nasa.gov/SeaSurfaceTemperature
[2]http://medsea-project.eu/
[3]http://www.emodnet.eu/med-sea-checkpoints
[4]http://www.emodnet.eu/northsea/home
[5]https://scholar.google.com/

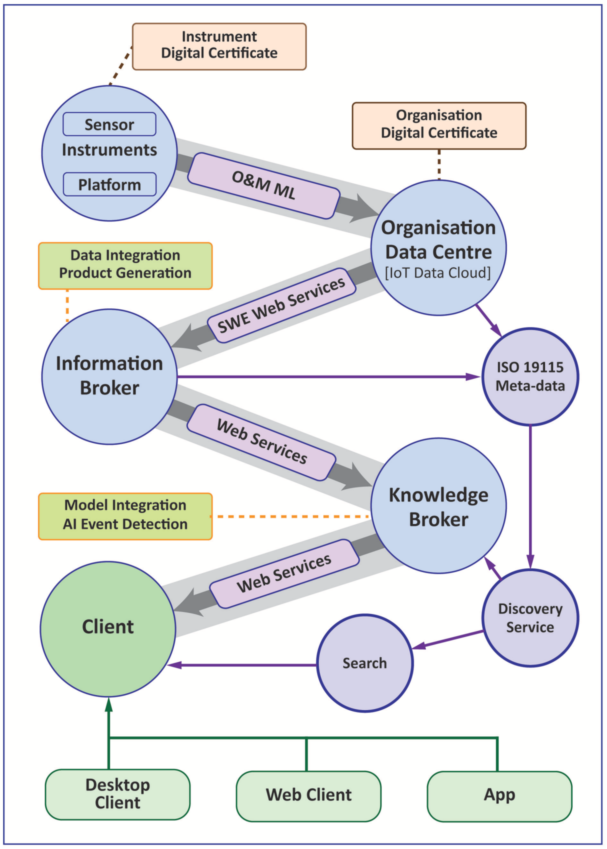

FIGURE 2 | Workflow diagram showing the role of information and knowledge brokers.

scientific literature and by providing tools, such as searching, download links and citation tools, to facilitate access and use of the data. The business model for the underlying publisher is either a "pay to publish" model where the author pays the journal to publish the article and generally access is free and open, or a "pay to access" model where the author gets published for free and so pays no fees to the journal but the journal charges for access. For Google the business model is increased web traffic and related advertising revenues along with providing public good.

The second example is AccuWeather[6], which exemplifies the operation of many other weather websites. Here the data is federated from a relatively small number of defined sources, mostly meteorological agencies, providing structured data streams, either for free or for a small fee as part of their charter. These sites add value by presenting the data in easy-to-use ways, by combining data from a number of data streams (such as up-to-date temperatures, medium- and long-range forecasts, weather radars, etc.) and by using sophisticated delivery platforms (Apps) to allow users to tailor the information they want (such as by defining locations of interest, display units and updates/alerts).

Another example is from the financial world. The StockCharts[7] site again uses a small number of federated, well-defined, machine-readable data streams to drive complex charting and analysis software. The site adds value through the analysis and charting engine but also by allowing extensively customization of the data. Users can annotate charts, construct watch lists, create alerts and notifications and access social media through blogs and on-site forums, where the user can gain and distribute knowledge relevant to their interest or need. This allows the construction of a sophisticated knowledge system around the source data via complex user-defined visualizations combined with the ability to access and contribute to a knowledge community.

The most sophisticated examples given are all based on a similar model of how data is sourced, accessed and then transformed into information for the user to extract knowledge from. The models typically include the following components or attributes:

1. While there may be many data sources, they are federated through a small number of providers, brokers or "clearing houses," allowing services to be built around a relatively small number of providers;
2. The data are pre-processed and packaged into standardized products that are structured to reflect the information contained within the data (for example, ocean temperatures can be processed into daily averages, climatologies, hot spot values, temperature accumulation values, surface values, daily min/max, etc.);
3. Full metadata is provided in a machine-readable form so that data discovery can be done via automated harvesting rather than manual searches;
4. Visualization and analysis engines are used to allow user interaction with the data such as extrapolating trends, setting alerts for user defined events (e.g., temperature thresholds being exceeded), producing climatologies and other statistics;
5. Models are used to synthesize data, to fill holes (such as the Buoyweather site, which uses models to deliver location-specific forecasts) and to provide higher level products such as forecasts;
6. A range of other resources are presented, in particular access to a community of practice, that allows the user to extract and create knowledge and associated value;
7. The systems use sophisticated platforms, such as Apps, to deliver content where the user can define a knowledge environment in which the information is contextualized and delivered.

A workflow that supports these ideas is shown in **Figure 2** where information and knowledge brokers federate data from a number of sources, process it into standardized products and then deliver these via services to a range of clients.

[6]https://www.accuweather.com/

[7]https://stockcharts.com

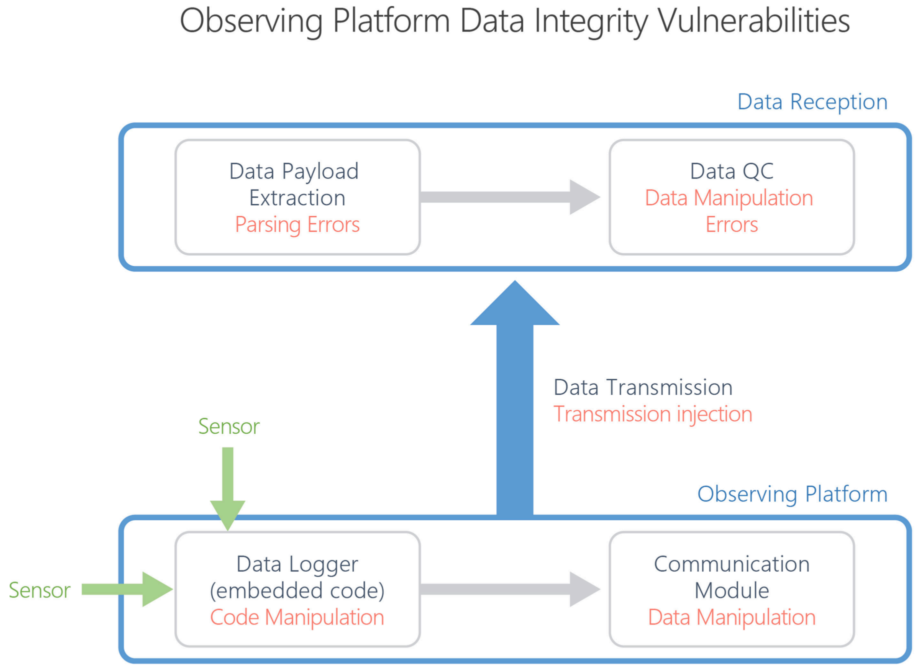

FIGURE 3 | Data integrity vulnerabilities in an example data workflow scenario.

The best example of data democratization is Google Earth[8]. Google Earth, via the Google Earth Engine, Google Earth client and Google Maps, uses many of the components of the other examples, such as a few federated sources of source data and complex visualizations, but extends these in unique ways that together have changed how people access and use spatial data.

These include:

- The user is totally abstracted from the source data (satellite images) with the system providing the initial processing and presentation. The user just gets to interact with the information in the system, not the data.
- The system allows extensive customization by the user with the ability to add layers, points, images and overlays easily so that, like the financial systems, the user creates a knowledge environment that reflects and contextualizes the knowledge they need to extract from the information;
- Google has built an easy to use import/export format (KML/KMZ), which allows other systems to integrate into their platform; this in particular allowed other companies and agencies to interact and be part of the information system;
- Google also created and promoted a full open API, allowing others to build systems and solutions around Google Earth and to build knowledge solutions that add value and which reflect a particular need or community;
- Google created and made freely available a range of clients from "thick" traditional PC clients to "thin" web systems to Apps, allowing anyone to use the system.

[8]https://www.google.com.au/earth/

The key point is that Google has abstracted the user from the source data and all of the complexities of purchasing, accessing, storing, processing, and visualizing satellite data. It then made the system open, via the API, the KML/KMZ import/export file and by making a range of clients available for no cost, which gave a path for the commercial and other sectors to invest in the system.

A key part of the above examples is the idea of a broker or clearing house. Brokering, in this instance, is accomplished by bridging technology that spans the gaps between the conventions of two different disciplines, enabling interoperability without levying additional requirements on either end (Nativi et al., 2013). In this role, brokers are able to unify or cross-map differing standards, formats and protocols, add value by enabling data discoverability, map domain specific knowledge and terminology across disciplines, and provide tools for data uptake and use. Effectively data brokers provide an interoperability layer by abstracting the input and output layers from each other, allowing users from one domain to access and use data from another.

This model however, has a number of potential issues. The first revolves around data quality, security, and provenance. Unlike relatively simple share price data, the collection, processing and use of environmental data is often complex, with a knowledge of the domain required to understand what is and what is not appropriate use. The potential for misuse, intentional or otherwise, is significant (as it is with share price data, which has extensive legal controls around access and use). The act of federating the data means that the connection between the data provider and the data user is lost, along with the ability to communicate the limitations, assumptions and complexities of the data to the end user. In science this is problematic;

indeed, many meteorological agencies are exempted from legal responsibility for the forecasts they provide for this very reason.

The second problem is more practical; how to build and sustain such a system. While much of the ocean data collected is amassed by publicly funded agencies, they are often either not operational agencies (and so not set up to deliver operational data products) or the data is collected under complex project arrangements that vary in life-span, resourcing and activity. Unlike the meteorological community, where there are agencies funded to produce publicly-available long-term data sets, the ocean community is more fragmented with responsibility shared across a range of research and operational agencies. Coupled with this is a complex political and funding landscape that makes it hard to establish and sustain multi-decade programs and infrastructure.

Developing a business model that supports and sustains data and information systems is not trivial and, while the monetization of data is not an area which the science community tends to explore, it is one that needs to be considered. Partnerships with the commercial sector are one way to build sustainability models that ensure continuity of data and information although reliance on a commercial partner has its own issues.

Importantly, the framework needs to also work in reverse. The framework needs to provide information to data custodians about who is using their data, what pathways and workflows they are using, what end products or information are being generated and what value is being created. The framework needs to be structured so that there are feedback components that measure attribution and deliver credit. Coupled with this is the idea of governance; how the various parts of the framework are governed, controlled, updated and maintained and how credit, resources and attribution are generated and delivered. To be sustainable every party involved needs to understand "what's in it for them"; that is be able to measure the value generated by being an active partner in the framework and how this translates into real-word resources and returns.

USER TRUST—DATA INTEGRITY AND SECURITY

Users of scientific or operational data retrieved from credible institutions expect it to accurately represent the phenomenon that was measured in the field or the laboratory. Following collection, the transmission, quality control, and all subsequent processing of this data should not detract from its accuracy. Such quality requirements are also held by data providers, who build their reputations around the validity and verifiability of their holdings. Quality data typically results from the application of community best practices across its lifecycle. Similar community standards also guide the documentation and contextualization of data, as the usability of even the best data is compromised without well-structured metadata and descriptions of provenance. Ensuring the integrity of the data (avoiding data corruption) is especially important for data that are to be stored in perpetuity and intended for future reuse. Integrity and consistency build a foundation of trust essential for information to be used in policy formation and for reliable monitoring of change.

While not an exhaustive treatment, this paper highlights the critical importance of data integrity and its impact on users' trust. A timely and important example involves the data used to understand the anthropogenic effects on our environment and climate. Any malicious attempt to cast doubt on climate science simply has to undermine the integrity of a discipline's data, or even a relatively minor fraction of it. The well-publicized "Climategate" event is indicative of the distraction that can be caused by casting doubt on data or its providers. To guard against such efforts, data integrity has to be transparently confirmed, corroborated, and well-documented throughout its lifecycle. This documentation needs to be readily accessible to the public as part of standard provenance metadata. Where possible, the provenance and quality control data should be bound with the raw data (e.g., via digitally signed data sets and with the provenance and data set QC data embedded in the raw data format) rather than exist in separate metadata systems. In the latter case, key metadata on provenance and quality can too easily be decoupled from raw data sets, to the detriment of all.

Data integrity can be affected through the entire lifecycle of the data, from the initial measurement, to the logging, through the remote platform transmission and payload decoding, to the quality control and long-term storage (see **Figure 3**). To a large extent, data integrity preservation is integrated into the various technical tools used to move data through its stages of the data lifecycle. For example, rsync and sftp include built-in data integrity checks during file operations. However, not all tools do this and it is evident that gaps or vulnerabilities exist at various steps of the data lifecycle that can potentially affect data integrity.

Internet Connected Instrumentation

Increasingly, scientific and operational instrumentation is connected directly to the internet via Wi-Fi, cellular, or satellite communications. These so-called Internet of Things (IoT) devices commonly use off-the-shelf technologies for data collection, encryption and transmission. This approach differs from comparable instrumentation and data logging devices from previous generations. While the promise of low-cost, easily configured and deployed devices is attractive to the ocean community for obvious reasons, IoT security is in its infancy. IoT devices with UNIX-like operating systems provide all the benefits and weaknesses of a typical desktop machine. Software vulnerabilities of IoT devices have become a prime target for malicious operators looking for ways to gain tangible benefits or disrupt the system for its intended user. Systems with no traditional operating system, or "bare-metal" IoT devices, can be similarly exploited.

Observing Platform Connectivity

Communications from observing platforms to data centers use a variety of technologies and protocols. While this paper cannot discuss the security profile of all communication protocols, we will highlight overarching themes and considerations. A major consideration for the data community is the risk that the communication platform and protocol presents not only to the integrity of the data while in communication transit, but also the vulnerability of the observing platform technologies, such as the data logging platform or sensor, discussed above. The objective is to ensure safe passage of the data, but also to ensure the communication technology is adequately detached from others on its platform to prevent its use as a vector by which the data collection platform is compromised. Attempted compromises of popular satellite communications platforms are well-documented. Global Wi-Fi is an exciting promise for operators on remote observing platforms but the application of off-the-shelf technologies demands data transmission security best practice to ensure secure passage and preserve the integrity of the data received by observing system operators. Safe passage of data is not unique to data platform operators, and industry practices, such as BlockChain, should be investigated and deployed where applicable. These methods should be cataloged and preserved in the platform metadata.

Vulnerability Management

Software solutions, such as operating systems, IoT device drivers, encryption libraries and data analysis applications are used at virtually every stage of ocean observation and data dissemination. Like nearly all software, these solutions contain security vulnerabilities and are therefore a potential entry point for a breach where malicious code or actors could compromise the data or systems. Further, even otherwise secure software can become vulnerable when configured or operated incorrectly.

In order to manage these vulnerabilities, system owners should have a process in place for detecting, tracking, prioritizing and remediating them. Should one or more of these vulnerabilities be exploited and result in an incident, the system owner should have an incident response process. Guidelines for these controls are outlined in NIST SP 800-53 Rev. 5. In the same way, groups that develop software solutions should follow a secure development process in order to minimize the number and severity of vulnerabilities. Guidelines for these controls can be found in NIST SP 800-64 (Kissel et al., 2008).

Data Quality Control (QC)

Data quality control seeks to identify and highlight data elements unrepresentative of the environment measured or outside the expected ranges produced by a processing routine. Best practices for data quality control are well-documented for many variables, but often scattered across the web. To help remedy this, the UNESCO/IOC-IODE Ocean Best Practices system[9] is consolidating access to these and other methods in a sustained archive (as described in section Developments in Tools and Standards). As these best practices become more systematically archived and available, the community should embrace well-established and uniquely referenceable QC processes. QC is a critical step to identify deviations from established norms in data. Integrity of processes and workflow elements discussed above should eliminate any concerns about unintended or malicious manipulation of data. The lack of these controls can cast doubt not only on a simple variable, but an entire data collection.

Long-Term Archives

Formal long-term archives play a critical role in ensuring data integrity for many data sets, for many users, over many generations. Many or perhaps most formal environmental data archives attempt to adhere to the standards and practices documented in the Open Archival Information System Reference Model (OAIS-RM[10]). The OAIS-RM establishes a set of responsibilities and functions that an Archive should commit to and perform, along with a common terminology for discussing these archival functions with stakeholders. Within the OAIS-RM, clear functions designed to assure data integrity (what the OAIS-RM calls Data Fixity) are included, and Data Fixity documentation is a key component of the Preservation Description Information (PDI) for every archival package.

While archives ensure Data Fixity, or integrity, in multiple ways, they also address other important types of PDI to ensure data remain useful and meaningful over time. Even if actual bit-level corruption is avoided, data loss can occur through other means. In addition to Data Fixity information, OAIS archives also work to ensure every archive package includes Reference, Context, Provenance and Access Rights Information at a minimum, to ensure data remain viable over the long term. Reference information includes the use of persistent identifiers like Digital Object Identifiers (DOIs) and taxonomic identifiers to describe and uniquely reference the archived content. Context information addresses why the data were collected and how they relate to other archived packages. Provenance information captures the history of the preserved data, and, via an Access Rights document, details who can access and interact with the data. Without all this information, data "corruption"—in the sense of losing the ability to trust the data—will occur.

The importance of archives, and the trust users place in them, has led to a range of independent archive certification processes. A popular example is the Core Trustworthy Data Repository certification[11], offered by the Data Archiving and Networked Services archive and the International Council for Science (ICSU) World Data System (WDS). Together, the OAIS-RM and the various certification processes give users confidence that critical issues such as data integrity have been addressed by the archive.

End User Data Delivery

Ambiguity caused by multiple data centers and third-party hosts having different versions of data is becoming an issue requiring management. If the data are to be used in decision making then users need to be sure they have the definitive version. When copies of data are re-exposed to the web via third parties there is a long-term overhead in ensuring that the most pertinent version of data is maintained. Distributed ledger technology such as Blockchain may be a potential solution to this issue (see: IEEE special report on blockchain[12]). In a distributed ledger

[9]http://www.oceanbestpractices.org

[10]https://public.ccsds.org/pubs/650x0m2.pdf

[11]https://www.icsu-wds.org/services/certification

[12]https://spectrum.ieee.org/static/special-report-blockchain-world

data are effectively assigned a fingerprint, which evolves as data versions evolve. This allows full data lifecycle and versions to be understood by users. The technology is mature for applications like Bitcoin but untested for tracking data provenance. There are also key questions to address such as: Is the high computation and energy cost justifiable for our applications? Can this process be done at sensor level, to cover the full data lifecycle? Also, the data become immutable when placed in a distributed ledger system. This is good from the perspective of long-term integrity but care is required with personal or sensitive data.

ENABLING TECHNOLOGIES

Oceanographic data are disseminated and exposed to the web at a range of levels from local, single institution websites and services to regional scale infrastructures and activities. Regional level infrastructures and activities include National Ocean and Atmosphere Administration (NOAA), National Centers for Environmental Information[13] (NCEI) and the developmental EarthCube[14] project in the USA, SeaDataNet[15] and EMODnet[16] in Europe, and the Australian National Data Service[17] (ANDS) and the Australian Ocean Data Network[18] (AODN). Despite continental boundaries, projects such as the in Ocean Data Interoperability Platform[19] (ODIP) work to harmonize international data efforts in the marine community. This section will describe many of the technologies used to harmonize data exposure to the web and emerging trends.

Developments in Tools and Standards

The technologies that will underpin automated data collection, processing and dissemination have been evolving for the last two decades and currently exist across a range of maturity levels. This section will focus on key enabling technologies that have the potential to underpin the data revolution this paper presents, looking at current technology before moving on to look at trends and developments.

A key advance is the introduction of Application Programming Interfaces (API). An API is a set of functions and procedures for creating applications that access the features or data of an operating system, application or other service. The modern API was first demonstrated by Roy Thomas Fielding in 2000 (Fielding, 2000), with commercial applications introduced by eBay and Amazon later that year. APIs are now ubiquitous on the internet. Their key benefit is in allowing services and data hosted by an organization to be accessed "machine to machine"; an example would be the display of dynamically sourced data from one organization on another organization's website, connected using common protocols.

The use of standardized services places new requirements on how data and information are exposed to the web, as the content has to be machine readable. A simple example: what is Practical Salinity called within my dataset? Numerous terms have been used that are readily understandable to the human reader e.g., psal, salinity, Salinity, sal, etc. However, these are subject to typographic errors and ambiguities e.g. the salinity reference scale associated with a particular data channel. Controlled vocabularies have been introduced to address these issues, e.g., the Climate Forecast (CF) standard names (sea_water_practical_salinity[20]). or the European P01 vocabulary used in the SeaDataNet infrastructure (PSALST01[21]). In the case of SeaDataNet, the vocabularies are audited and published on the NERC Vocabulary Server (NVS 2.0) in the machine-readable, Simple Knowledge Organization System (SKOS) with standardized APIs for querying and delivering terms (REST, SOAP and SPARQL). Many of these vocabularies are also semantically linked to local or external vocabularies, so a user (or machine) can identify similar or related terms. Importantly, the standardization and formalization of descriptors using controlled vocabularies and SKOS modeling is providing the foundation for further innovation in ocean informatics. The application of knowledge representation methods and highly expressive semantic technologies using the Web Ontology Language (OWL) is allowing machine agents to more flexibly handle multi- and interdisciplinary data (see Trends and the future of tools and standards).

Further to the use and importance of standards, standardizing the encoding of metadata and data themselves will be crucial if data are to be readily usable by machines or dataset aggregations. The Ocean Data View and SeaDataNet activities have introduced a standard ASCII representation of data. For multidimensional and larger datasets based on binary formats, key advances have included the introduction of the CF-NetCDF standards and the Attribute Convention for Dataset Discovery (ACDD). Elements of CF-NetCDF and ACDD have been used in NetCDF formats developed by community observing programs (Ocean SITES data management team, 2010; Argo Data Management Team, 2017; EGO gliders data management team, 2017). Concurrently, the OGC has developed Sensor Web Enablement (SWE) standards including SensorML for sensor metadata and Observations and Measurements (O&M) for sensor data. These are XML-based representations but are readily converted to other formats such as JSON. The breadth of data and metadata standards are described in **Table 1**.

Best practices (Pearlman et al., 2017a) complement standards in supporting improved interoperability and data/information exchange. A community best practice is defined as a methodology that has repeatedly produced superior results relative to others with the same objective. To be a best practice, a promising method will have been adopted and employed by multiple organizations. Best Practices may occur in a number of areas—standard operating procedures, manuals, operating instructions, etc., with the understanding that the document content is put forth by the provider as a community best practice (Simpson et al., 2018). As with standards, the benefits for ocean data include improved consistency and interoperability

[13]https://www.ncei.noaa.gov/
[14]https://www.earthcube.org/
[15]https://www.seadatanet.org/
[16]http://www.emodnet.eu/
[17]https://www.ands.org.au/
[18]https://portal.aodn.org.au/
[19]http://www.odip.eu/
[20]http://cfconventions.org/Data/cf-standard-names/58/build/cf-standard-name-table.html
[21]http://vocab.nerc.ac.uk/collection/P01/current/PSALST01/

TABLE 1 | Table describing the summary of data and metadata standards presented in this paper.

Standard	Function	Impact	Status	Link/Reference
OGC SWE/SML and O&M	The OGC's Sensor Web Enablement (SWE) standards enable developers to make all types of sensors, transducers and sensor data repositories discoverable, accessible and useable via the Web.	Part of an integrated framework, from sensor to user with delivery of real-time data to the Web.	Implementations tested in the EU for fixed and mobile platforms and multidisciplinary data.	Standards http://www.opengeospatial.org/standards/sensorml http://www.opengeospatial.org/standards/om Tool/SensorML Editor https://github.com/52North/smle Tool/Viewer https://github.com/52North/helgoland
OGC SensorThings API Part 1: Sensing	Complementary OGC standard for sharing observation data collected by internet of things devices.	Additional OGC standard for lightweight access to observation data streams.	Implementations are available.	Standard: http://docs.opengeospatial.org/is/15-078r6/15-078r6.html
MQTT	Lightweight data transmission protocol following a publish/subscribe pattern.	MQTT allows the efficient integration of real-time observation data streams into distributed architectures.	Broad support by implementations. Successful tests in the marine community	Standard: http://docs.oasis-open.org/mqtt/mqtt/v3.1.1/mqtt-v3.1.1.html
OGC WMS	The OpenGIS Web Map Service Interface Standard (WMS) provides a simple HTTP interface for requesting geo-registered map images from one or more distributed geospatial databases.	Provided a common standard for serving geo-registered map images to the web.	Standard actively governed and maintained by the OGC	http://www.opengeospatial.org/standards/wms
W3C Linked Data	Linked data is a set of design principles for sharing machine-readable data on the Web for use by public administrations, business and citizens.	Flexible and seamless data integration. Reuse of ontologies and vocabularies. Semantic unambiguity. Machine readable and understood data. Discoverability.	DBPedia and BBC are some of the most well-known applications of Linked data. The British Government created the UK Government Linked Data Working Group to publish government linked data.	https://www.w3.org/DesignIssues/LinkedData.html https://ckan.publishing.service.gov.uk/ http://linkeddatabook.com/editions/1.0/
ISO 19115	Defines the schema required for describing geographic information and services.	Provides a common schemed geographic information and services in the environmental community.	Is a formal published standard.	https://www.iso.org/standard/26020.html
Dublin Core	Dublin Core is a metadata standard for making statements about resources.	Made standardized annotations of resources on the web. Discovering resources on the web made easier.	Active community: http://dublincore.org/	http://dublincore.org/documents/2005/08/15/usageguide/ http://dublincore.org/documents/dcmi-terms/
DarwinCore	Darwin Core is a set of standards to facilitate the exchange and integration of biodiversity data and associated information	Plays a fundamental role in the sharing, use and reuse of biodiversity data worldwide and across specialist domains; enables the assembly of hundreds of millions of species occurrence records in DwC format through the Global Biodiversity Information Facility GBIF.org.	Active community. New activities focusing on controlled vocabularies and semantic interoperability.	http://rs.tdwg.org/dwc/ https://www.gbif.org/darwin-core

(Continued)

TABLE 1 | Continued

Standard	Function	Impact	Status	Link/Reference
Climate Forecast (CF) compliant	The conventions for CF (Climate and Forecast) metadata are designed to promote the processing and sharing of files created with the NetCDF API.	Enable a base level of interoperability between NetCDF data made available by environmental data community.	Actively governed by the CF community	http://cfconventions.org/
NetCDF(Network common data format)	NetCDF is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data.	Along with the HDF formats NetrCDF enabled representation of multi-dimensional scientific data in data files without the constraints of that ASCII formats impose.	Actively governed by Unidata	https://www.unidata.ucar.edu/software/netcdf/
The Attribute Convention for Dataset Discovery (ACDD)	ACDD describes attributes recommended for describing a NetCDF dataset to discovery systems such as Digital Libraries. THREDDS and other tools can use these attributes to extract metadata from datasets, and exporting to Dublin Core, DIF, ADN, FGDC, ISO 19115 and other metadata formats.	Similar impacts to CF compliance.	The ACDD community and governance are active with the last update in January 2017. ACDD is implemented consistently in NOAA data. Partial implementation has been achieved within GOOS networks NetCDF versions of data.	http://wiki.esipfed.org/index.php/Attribute_Convention_for_Data_Discovery_1-3
Plain text and Comma Separated Values (CSV) formats	Human-readable files that are not structured or formatted and are generally delimited by characters such as tabs, spaces or commas. They are typically used for tabular data.	Due to their simplicity, these formats have been widely adopted in the biogeochemical and biological communities.	Most proprietary software have applications that can read encodings of plain-text and CSV (e.g., Microsoft Windows Notepad/Excel etc.)	
SeaDataNet ODV ASCII and NetCDF formats	The SeaDataNet ODV import format is a version of the ODV version 4 generic spreadsheet format modified with some of the flexibility removed and to carry additional information required by SeaDataNet.	ODV ASCII is used widely within the ocean biogeochemical community where data in binary formats pose a technical barrier to users. ODV NetCDF is a CF-compliant NetCDF version.	Has current governance and within the European SeaDataNet infrastructure where the format is a primary exchange format.	https://www.seadatanet.org/Standards/Data-Transport-Formats
Schema.org	Schema.org is a collaborative, community activity with a mission to create, maintain, and promote schemas for structured data on the Internet, on web pages, in email messages, and beyond..	Set of vocabularies that allow tagging up of webpages, datasets enhancing their discoverability and representation by google search engine.	Supported and used by Google, Bing, Yandex and Yahoo. Contributors: https://schema.org/docs/about.html	https://schema.org/

Because of content size limitations the list is not exhaustive and is representative of the data standards described in this paper.

among measurements on a local to global scale, increased dialog and cooperation among experts and a reliable base to make comparisons addressing evolution of the ocean ecosystem. Best practices benefit day-to-day operations by reducing duplication of effort and unneeded repetition of learning processes. They create a knowledge base to speed development and improve efficiency. The difference between standards and best practices is the process of consensus building, adaptation and adoption. Standards generally take years to create and adopt once the underlying methodologies are accepted by the community. Best practices have a faster adoption period and can more readily adapt to emerging technology and embody new capabilities. Another factor for standards is that they may not be detailed enough such that implementations by different organizations are interoperable. A combination of best practices and standards may be required for certainty of interoperability.

Brokering data to form new products or services is not a new concept in the marine community. The promotion of standardized data and metadata services can be hastened via the use of community or commercial software. The SeaDataNet infrastructure combines metadata and data from over 20 data centers in a single portal. This is then used by EMODnet in data products. The ERDDAP software developed by NOAA is a different technical solution that enables the brokering of data between data centers with no separate dedicated infrastructure. An example based on OGC standards is the 52°North Sensor Web Suite, which provides an off the shelf OGC SWE capability. The concepts have been applied at the global scale by the International Oceanographic Data and Information Exchange (IODE) Ocean Data portal and by Group on Earth Observations (GEO) Global Earth Observation System of Systems (GEOSS) GEO Discovery and Access Broker (GEODAB). The GEODAB handles brokering of metadata and data, adapting formats to the user's discipline. A significant challenge with such brokering is ensuring unambiguous provenance and that definitive versions of data and metadata are provided as discussed in Democratization of data. Selected tools and software currently available in the marine community are summarized in **Table 2**.

When comparing open source and proprietary (closed source) software, different aspects need to be considered. The licenses for each type of software differ. While open source code is available to the public and can/must be freely shared, proprietary software's source code is usually only available to the vendor. In case of open source software, openness of the code allows community-driven development of new and extended versions. If a company offering a proprietary software package closes down, the development is usually discontinued (unless another entity acquires the rights to the software). In case of open source, the available source code facilitates the continuation of the development by other companies and organizations (even in-house development by companies using the software is possible). For both types of software there is often a broad range of companies providing professional support. Typical examples of open source software with broad support are PostgreSQL and the projects managed by the Apache Software foundation. In addition, developer communities are an additional source of (often free) support for open source software. In case of proprietary software, the support is usually provided by the vendor or authorized service providers with different levels of available (often paid) support packages. In either paradigm, if we are to depend on the software to give a stable operating environment, the creation process should be performed in a stable manner, guided by well-documented and accepted best practices.

Trends and the Future of Tools and Standards

The technologies and standards used to disseminate data must address the needs of both user communities and data integrators. The term "user communities" encompasses groups such as observation and data scientists, application and policy experts and teachers. Interfacing with all these groups will require collaboration between providers, users and standards communities. In pursuit of this goal, development is occurring on the World Meteorological Organization (WMO) Information System (the next step in the evolution of the Global Telecommunications System). Further, Global Ocean Observing System (GOOS) are defining and developing the EOVs, SeaDataNet and EMODNet are moving to cloud-based services and user-defined data products, IODE—which provides repositories for data, standards, best practices, and community adopted practices—agreed on CF-NetCDF formats. In addition to existing users, there are private sector actors who will readily use any freely available open data. To rally efforts to open and interlink distributed data stores, Wilkinson et al. (2016) introduced the FAIR data principles (Findable, Accessible, Interoperable, Reusable). The use of controlled vocabularies and ontologies, standardized data, and standardized access protocols, created either as standards or operationally adopted as best practices, are central to successfully implementing the FAIR principles to support widespread uptake and long-term use.

To open data as close to its source as possible, data and metadata standards are being applied closer to the sensor in the data life cycle. Monterey Bay Aquarium Research Institute (MBARI) has developed the OGC PUCK protocol, enabling a sensor to forward its own metadata in OGC SensorML format. The NeXOS project developed this further with the integration of optical and acoustic sensors on ocean gliders, profilers and vessels of opportunity (Delory et al., 2017; Ferdinand et al., 2017; Martinez et al., 2017; Memè et al., 2017; Pearlman et al., 2017b; Delory and Pearlman, 2018; Río et al., 2018; Simpson et al., 2018). Such technology will enable the automated installation, processing and dissemination of data via standard software suites and tools making the management and integrity of provenance metadata more robust. Adoption by industry has been slow, possibly because demand needs to come at the procurement stage as a broad requirement from marine community. Infrastructures like Ocean Observatories Initiative (OOI), North-East Pacific Time-series Undersea Networked Experiments (NEPTUNE), Integrated Marine Observing System (IMOS), and European Multidisciplinary Seafloor and water column Observatory (EMSO) can leverage this.

Due to decades of hardware miniaturization and widespread uptake, the majority of humans now carry a powerful connected computing platform. This technology has proved attractive not only because the devices are handheld, but also because their software has either adapted to people's interests or created new

TABLE 2 | Table summarizing selected tools and services applicable to the content presented in this paper.

Tool	Function	Impact	Status	Link/Reference
ERDDAP	An open source data server that enables users to visualize data and download subsets of gridded and tabular scientific datasets in common file formats. It acts as a data broker between a variety of different types of client programs (web browsers, IDV, Matlab, netCDF programs, ODV, WMS clients, etc.) and data servers (e.g., OPeNDAP, SOS, OBIS	Used widely, ERDDAP makes different types of remote data servers interoperable without the complexity of dealing with different request formats, thus enabling the aggregation of large datasets and easy integration into new user communities	Installed by over 70 networks worldwide, including Ocean Tracking Network (OTN), a global aquatic animal monitoring platform and ARGO, a global array of oceanographic 3,800 free-drifting profiling floats that measure temperature and salinity of the ocean. Currently sustained by the National Oceanic and Atmospheric Administration (NOAA).	https://coastwatch.pfeg.noaa.gov/erddap/index.html https://coastwatch.pfeg.noaa.gov/erddap/download/setup.html
THREDDS	The THREDDS Data Server (TDS) is a web server that provides metadata and data access for scientific datasets, using a variety of remote data access protocols.	Provides students, educators and researchers with coherent access to a large collection of real-time and archived datasets from a variety of environmental data sources.	Maintained by Unidata, emphasis has moved to ERDDAP.	https://www.unidata.ucar.edu/software/thredds/current/tds/
OPeNDAP	OPeNDAP data server which makes local data accessible to remote locations regardless of local storage format.	Used widely in earth science, it provides researchers with access to remote data sets or large data collections.	Used to provide access to large data collections, including global climate models (Earth System Grid Federation (ESGF)) and sea surface salinity data sets (NASA Aquarius mission). Currently, developed and sustained by the non-profit, OPeNDAP, Inc.	https://www.opendap.org/
FTP	The File Transfer Protocol (FTP) is a standard network protocol used for the transfer of computer files between a client and server on a computer network.	Enabled the GOOS community to readily serve observing programme data to the science community.	Used operationally by many of the GOOS networks to serve data e.g., Argo, OceanSITES, Ocean Glider Network.	
OAI-PMH	The Open Archive Initiative—Protocol for Metadata Harvesting (OAI-PMH) is a protocol specification for exchanging and harvesting an object's (resource) metadata (record) between data and service providers.	OAI-PMH requests are expressed as HTTP requests enabling it to be easily harvested (e.g., by internet search engines) or integrated into remote applications (e.g., search indexes)	Many implementations used in the bibliographic domain (e.g., National Library of Congress, US).	https://www.openarchives.org/pmh/
OGC SWE/SOS Service	The OGC's Sensor Web Enablement (SWE) standards enable developers to make all types of sensors, transducers and sensor data repositories discoverable, accessible and useable via the Web.	Part of an integrated framework, from sensor to user with delivery of real-time data to the web.	Implementations tested in the EU for fixed and mobile platforms and multidisciplinary data.	Standard http://www.opengeospatial.org/standards/sos Code https://github.com/52North/SOS
Github	Cloud-based file versioning services, integrated with the desktop Git versioning application. This is used largely for software code management.	The socializing of software code. Promotes open-source collaboration through ease of access.	Used by professional organizations and research institutes around the world.	https://github.com
Python	Open-source programming language. Highly adopted within Data Science, engineering and scientific communities due to its many actively maintained libraries	Python (along with tools and languages like R-Studio) are removing the software license fee barriers on scientific software	Used by scientists, engineers, software developers, data scientists, website designers.	https://www.python.org/

Because of content size limitations the list is not exhaustive and is representative of the type technologies described in this paper.

capabilities (e.g., communication, navigation through interactive maps, real-time news feeds, entertainment) at little or no cost (but with privacy concerns) and become agnostic to the diversity of operating systems. Attempts to reach out to the public with content related to ocean observation and community-targeted data products are addressed in End user engagement, while most web-based applications are now available or deployable on handheld devices with little effort. The relevance of developing yet another application now seems to only depend on the existence of an identified need or activity and a community of users (e.g., citizen scientists, teachers, surfers) eager to test a new application on their device and feel part of a community. There is a world of opportunities for new services and potential for crowdsourcing—not so much for the funding of new projects but rather engaging with a large number of users to process large sets of complex information, such as for classification of key ocean features—a process that remains difficult to automate. Features extracted by users from pictures could in turn be used to produce large training sets for automated classifiers.

Feeding new applications, federated datastores allow linking of distributed data collections. ERDDAP allows for federation of instances by linking them through APIs, controlled by the ERDDAP admin. The end result is that users can access data from multiple datastores from a single portal or API while the data remains within the control of the experts (data centers). A federated system should always serve the latest version of the data, thus solving the "multiple copies" issues found in a traditional distributed system. While federation between the same software (ERDDAP to ERDDAP) is straightforward, federating between different systems using different software is more complex and relies on mapped—or, preferably, synchronized and co-developed—vocabularies and ontologies which describe the data itself in a machine-readable way. Indeed, communities which are more advanced in semantic data science have federated these descriptive resources themselves. A key example from the life sciences can be found in the Open Biological and Biomedical Ontology (OBO) Foundry and Library[22] Smith et al. (2007). This federation of coordinated and interoperable ontologies is guided by common development principles and core software, providing a relatively stable system for linking data. Through OBO ontologies such as the Environment Ontology (Buttigieg et al., 2016), which is coordinating content with standards such as the US Coastal and Marine Ecological Classification Standard[23] (CMECS) and the GOOS EOV Panels, this federation is now providing resources and best practices to support future innovation in ocean observation.

Ontologies provide the bridge between expert knowledge and the world of Open Linked Data, which is one of the core pillars of the Semantic Web, or Web of Data. The Semantic Web functions through links between datasets, understandable to machines as well as humans. Linked Data, a set of design principles for sharing machine-readable interlinked data on the web[24], provides the best practices for making these links possible.

A representative feature of linked data technology is the use of URLs, URIs, and IRIs as the unique, web-accessible data object identifiers, rather than simple textual names, which are prone to confusion across disciplines and systems. These function much like DOIs, but Linked Data URIs resolve to standardized formats (typically encoded in RDF) which describe their content to machine agents using ontologies and controlled vocabularies. Further, Linked Data stores can include links to other linked data URIs, providing structured access to complementary data and boosting discoverability. As a valuable bridge to practical ocean observing hardware such as sensor systems, the joint W3C (World Wide Web Consortium) and OGC (Open Geospatial Consortium) Spatial Data on the Web (SDW) Working Group developed a set of ontologies (SSN/SOSA) to describe sensors, actuators and samplers as well as their observations, actuation and sampling activities. Annotating sensor metadata and datasets with W3C-defined ontologies and domain-specific vocabularies and ontologies enhances discoverability, understanding and integration with other linked data. In the SenseOcean project, British Oceanographic Data Centre (BODC) used content negotiation to provide either SensorML, or Semantic Sensor Network (SSN) descriptions of sensor metadata. In the next decade, efforts to bridge these various activities and development communities must be intensified to provide thorough semantic alignment (so that the use of each solution can be evenly understood by machine agents) and, consequently, reliable data exchange. Upon this basis, oceanographic data will be more readily and coherently linkable to data in other domains such as socio-economics, governance[25] and health [e.g., The Monarch Initiative[26] (Mungall et al., 2017)], which are also adopting similar semantic standards.

Together, responsive, integrated, and expressive vocabulary and semantic services will not only allow data to be effectively linked within ocean science, but also to policy-relevant reporting frameworks as they emerge. This is key to ensuring that the products of ocean observing reach decision makers (and the data systems they interface with) in a timely and understandable form. Currently, the Essential Variables for the Ocean, Climate, and Biodiversity [EOVs, (Lindstrom et al., 2012) ECVs (Bojinski et al., 2014), and EBVs (Navarro et al., 2017), resp.] are important global targets to bridge observation, science, and policy in the marine domain. These variables have been selected to provide core insight into the planet's functioning in order to support policy development and assessment, compatible with local and regional frameworks. Through coordination projects such as AtlantOS[27], many of these variables have been mapped to the CF and P01 resources (Koop-Jakobsen et al., 2016) and their interrelations (Miloslavich et al., 2018; Muller-Karger et al., 2018) are being resolved and expressed in machine-actionable semantic resources for planetary science such as The Environment Ontology ENVO; Buttigieg et al. (2016).

Promisingly, these initiatives are converging with similar interoperability solutions emerging in policy-focused domains. For example, the UN Environment Sustainable Development

[22] http://www.obofoundry.org/
[23] https://cmecscatalog.org/
[24] https://ontotext.com/knowledgehub/fundamentals/linked-data-linked-open-data/
[25] https://ukparliament.github.io/ontologies/
[26] https://monarchinitiative.org/
[27] https://www.atlantos-h2020.eu

Goals Interface Ontology [SDGIO; UNEP (2015); Buttigieg PL et al. (2016)] uses OBO-compliant semantic web technology to create an interface between observational data sources and the indicators of the global Sustainable Development Agenda for 2030 (UN, 2015), including those for ocean health and biodiversity (SDG 14). Such connections will be key in linking diverse marine data to global reporting frameworks in the upcoming UN Decade of Ocean Science for Sustainable Development[28].

Machine-readability is the bridge to machine intelligence. With the advent of big data technology and development of SMART cities, artificial intelligence (AI) algorithms are being developed to automate routine decisions such as traffic control and adaptive public transport loading. Such concepts are transferable to marine applications such as SMART ports or SMART sea areas and the role of AI could include regulatory monitoring of hazards or pollution, reducing their cost.

Machine Learning is a branch of AI concerned with developing computer models that "learn" from data by analyzing existing data sets. These models can then be used to identify similar objects or patterns in other data. Currently the main application of AI is to identify objects in images, for example the use of Convoluted Neural Networks to automatically identify benthic types in coral reef survey images (Gonzalez-Rivero et al., 2016). New approaches are being trialed in numeric data where patterns in long-term environmental time series are being transcoded to a form that the AI can model and learn (Shang et al., 2014). The resulting models are able to identify underlying patterns in large volumes of data. These patterns may represent errors in the data, meaning that the AI is performing quality control, or they may represent interesting or new phenomena, making the AI an event detection agent. Machine Learning, by identifying patterns within data, provides new pathways for knowledge generation and in particular provides a new tool for dealing with large complex data sets.

In September 2018 Google launched its new dataset search service[29]. Similar to how Google Scholar works, Dataset Search lets you find datasets wherever they are hosted, whether on a publisher's site, a digital library, or an author's personal web page. The approach is based on the schema.org standard described in **Table 1** with clear guidelines for data providers. This represents a significant step toward the implementation of universal dataset discovery, and an interface for the ocean standards discussed above.

END USER ENGAGEMENT

The scope for high-throughput measurements of the marine environment has greatly increased in recent years, both for physical and chemical oceanography (OceanSITES, ARGO etc.) but also, more recently, for the observation of marine biodiversity. The increasing number of remotely operated sensors/sensor networks and the greater range of parameters coupled with more advanced observation technology, such as those based on molecular or imaging sensors to generate biodiversity data (Buttigieg et al., 2018; Stern et al., 2018), have also considerably increased our potential for analyzing a greater range of complex environmental/climate change related topics.

This means that data can, in theory, also usefully serve a larger number of potential end users. These include the scientific community, conservation practitioners and citizen scientists but also actors at the science-policy interface, who require more detailed monitoring of ocean processes to satisfy important policy drivers, such as the Marine Strategy Framework Directive (European Commission, 2008) or activities addressing, in a broader sense, the UN Sustainable Development Goals goals and targets for managing biodiversity (e.g., the AICHI targets). The latter require the development of National Biodiversity Action Plans, which in turn necessitate the collation and integration of biodiversity data sets from a range of disparate sources deploying different sample collection and analysis pipelines as well as different archival mechanisms with associated data management, analysis, archival and visualization issues.

However, the data sets emanating from a range of different measuring devices, particularly in the field of biology and ecology, while holding great analytical potential, also have increasingly complex metadata and are therefore not easily interpretable. To deal with these complexities, biodiversity-based long-term observation networks, such as Long-Term Ecological Research (LTER)/International LTER (ILTER), have already been established, although they are not yet dealing directly with issues around the integration of sensor-based high throughput data and their visualization and interpretation (and their marine component is currently relatively small).

User engagement therefore has to go beyond generating an interest into given data sets or research results. Indeed, the process of user engagement has become much more complex. It can include early consultation processes during the development phase of data systems and products (e.g., surveys, questionnaires, stakeholder meetings). Most importantly however, user engagement also encompasses the responsibility to ensure that data are correctly understood by different end users. This makes it necessary to monitor, document and archive (using standardized metadata protocols) all elements of the data lifecycle, from sampling protocols via the properties, precision and accuracy of different sensors to archiving in accepted repositories such as Pangaea or EMODnet's GEOSS Portal, and to make relevant metadata available in a well-organized and transparent form relevant to potential end users (Koppe et al., 2015).

The tailoring of products, whether observations or information, also needs to promote user uptake and employment of products. While this is supported by standards and best practices, the interface logic must be simple and intuitive. The data needs to come in widely-used, stable formats. In addition, access interfaces (which address both discovery and access of data and information) should also be intuitive. Users prefer widely accepted methodologies and formats.

Once such mechanisms are in place, data products can be tailored to different audiences, from the research community to the public to political stakeholders and those with reporting duties in support of different policy drivers.

In this way, we can enable existing and emerging observation and analysis networks, such as the European Ocean Observing

[28]https://en.unesco.org/ocean-decade
[29]https://toolbox.google.com/datasetsearch

system (EOOS), other regional ocean observing networks or IOC-UNESCO's TrendsPO, to deliver good data and data products maximizing the output from the largest possible number of data sources. Some examples of advanced data products for "manual" and/or sensor-based time series as well as other types of data, based on agreed and transparent metadata standards, already exist.

Use Cases

Deep Sea Observatories: Fram/Hausgarten (e.g., Soltwedel et al., 2013)

The mission of the FRAM programme (FRontiers in Arctic Marine Monitoring) is to support synchronous, year-round, integrated system observation in the Fram Strait and Central Arctic. The Fram Strait connects the North Atlantic and the Arctic Ocean, one of the fastest changing marine regions on Earth. Unlike the shallow water conjunction to the Pacific, this connection reaches 5,569 meters in depth and is thus the main region for exchange of water between the Arctic and the Atlantic Ocean. Cutting edge technologies are being used and developed to record EOVs to improve our understanding of the Arctic and its unique phenomena. FRAM consists of two Alfred Wegener Institute (AWI) long-term (∼20 years) mooring observatories in the West Spitsbergen Current and HAUSGARTEN, and involves a modern vision of integrated underwater infrastructure. Stationary devices are complemented with diverse mobile components such as deep-sea robots, ice buoys, and autonomously operating underwater robots that operate beyond HAUSGARTEN into the Norwegian Sea and the Arctic Ocean. FRAM technology provides large amounts of data. Building on this, FRAM now enhances sustainable knowledge for science, society and the maritime economy as it enables truly year-round observations from surface to depth in the remote and harsh Arctic Sea.

The sheer number and complexity of research platforms and their respective devices and sensors, along with heterogeneous project-driven requirements toward satellite communication, sensor monitoring, quality assessment and control, processing, analysis, and visualization led AWI to build the generic and cost-effective virtual research infrastructure O2A to enable the flow of sensor Observations to Archives. O2A is comprised of several extensible and exchangeable components as well as various interoperability services and is meant to offer practical solutions that support the typical scientific workflow, from data acquisition activities until the very last data publication.

Examples of O2A components are:

1. SENSOR and STREAM components designed to provide metadata on platforms, instruments and sensors along with near real-time data transfer solutions (currently more than 1,100 sensors have been registered);
2. DASHBOARD component offering dashboard-oriented monitoring solutions, which include graphing and mapping widgets among others;
3. VIEWER offering map-based visualization and analysis solutions;
4. repositories PANGAEA and EPIC for data and publications, respectively;
5. DATA portal as a one-stop shop web interface for disseminating scientific content associated with research platforms and thematically grouped data and data products.

In FRAM, and other multi-instrument, multi-user international projects based on O2A, the end user can rely on quality-controlled data with well-described, standardized metadata and can create custom graphics, data, images and text panels, etc. In each data panel the user can freely recombine available data, choose time periods and data granularity for their plots. They can also generate simple descriptive statistics. This facilitates easy data exploration and a means of quality control turning sensor diversity into an advantage. These combined data are an important basis for scientific studies, are supporting computer simulations of the Arctic ecosystem and improve validations of remote sensing products.

Coastal Observing System for Northern and Arctic Seas (COSYNA) (Baschek et al., 2017)

The COSYNA Observing System for Northern and Arctic Seas[30] (COSYNA) comprises a variety of terrestrial and underwater sensor systems for monitoring the marine coastal environment of the North Sea and Arctic Ocean. Both areas are "hot spots" with respect to global change in biodiversity and climate. The COSYNA system integrates a wide range of different sensor types, from coastal radar remote-sensing installations (to monitor currents in a large area) via ocean gliders (to scan a larger water body *in situ*) to specific fixed installations like poles, autonomous landers or cabled underwater observatories to monitor changes and dynamics in a specific marine environment (Baschek et al., 2017; Eschenbach, 2017). The COSYNA sensors are designed to be as close to fully automated as possible to provide real or near-real time information, short-term forecasts and additional data products. Closely related to the development of new sensor types and sensor carrier systems, improved methods and algorithms are developed to improve the quality of remote-controlled sensor data with a specific focus on a better understanding of the interdisciplinary interactions between physics, biogeochemistry and the ecology of coastal seas. Within this framework, new modeling and data assimilation techniques are also developed to better integrate observations and models in a quasi-operational system providing descriptions and forecasts of key hydrographic variables.

A key feature of COSYNA (as for FRAM) is that all data and data products have received automated quality control with quality control flags assigned accordingly and are freely available via the COSYNA portal. Detailed metadata descriptions are also available for each sensor. The end user can combine different types of data e.g., chlorophyll from sensors and remote sensing to produce map visualizations of the parameter in a given area. In addition, selected data from the COSYNA network are used to produce advanced products such as models of current fields in the German Bight, which are also freely available as time series.

The COSYNA system was implemented between 2010 and 2014 and has been followed up in further monitoring projects

[30]https://www.hzg.de/institutes_platforms/cosyna/index.php.de

like ACROSS (2014–2018) and MOSES[31] (2017—ongoing). All these projects have the central requirement that data coming from the different sensors must be shared across disciplines and therefore must meet the requirements of FAIR (**F**indable, **A**ccessible, **I**nteroperable, **R**eusable) datasets.

In addition to these complex integrated data systems, some specialized data products have also been developed that deal with a small number of parameters from very diverse data sources and providers, which have included considerable user engagement. One example is the IGMETS portal[32], which hosts visualization tools for hundreds of plankton time series at a global scale. Development of this portal involved input from two expert groups in the International Council for the exploration of the seas (ICES) and members of an IOC UNESCO working group but also included individual providers of biological, statistical and oceanographic expertise.

EMSO-Obsea: Cabled Underwater Coastal Observing System for Western Mediterranean (Aguzzi et al., 2011)

The Obsea observatory was deployed in 2009 with two main objectives: to study and monitor coastal process and biological habitat at the Catalan coast, and secondly to become a reference underwater test site for new instruments, sensors and also as a test site for new data communication protocols and data management (Río et al., 2014). The Obsea data management system is dealing with many different types of data, mainly physical parameters and biological indicators using video cameras. The observatory is already monitoring real time underwater noise and seismometry. Many interoperability experiments have been carried out using the observatory with the data produced available through European repositories such as EMODnet[33] or via public datasets in Pangaea[34]. This highlights the importance of generating unique identifiers (DOI) for data produced during an experiment where the same data may be held in multiple systems.

VISION FOR THE FUTURE

This paper has covered a broad range of themes, from introducing the democratization of data, to requirements around the integrity of data, describing enabling technologies, and actual use cases. This section summarizes the main points as succinct vision statements.

- Data and metadata are available via standards-based secured API's, using FAIR principles to define data services, to enable new and existing communities to develop their own bespoke web portals, applications, and value-add systems, based on a single digitally-signed quality-controlled data source, to deliver greater uptake, use and value from the collected data.
- Data sets, models and data products are uniquely identified using Digital Object Identifiers (DOI's), digitally signed using certificates to identify source and provenance (including identifying the definitive version of a data set), quality controlled using documented best practice systems (including Quality Control as a Service—QCaaS) with the QC data traveling with or linked to the source data, full machine readable metadata available that includes appropriate use and attribution, as source components of new work-flows.
- Common harmonized standards and reference models, including test and validation environments, for describing metadata and data, allowing interoperability between different communities and disciplines.
- Users can access, extract and understand an unambiguous provenance for all types of data used, versions it originated from and other versions it has been incorporated into, to increase trust into the data and enhance usability.
- New information workflows, based on a standards-based service-based architecture, to move from a portal to a services-based model where users pull knowledge rather than consume pre-built products and so data is used and value added beyond its initial scope and discipline. This will have implications for data provenance, quality control, licensing and appropriate use.
- New methods for data discovery and access, such as discovery and aggregation of data via commercial search engines, continued development of open extensible platforms, such as Google Earth, and the development of sophisticated knowledge clients, including mobile apps, to replace the current Portal-and-Download model, to simplify and extend access for new and existing users
- To have a modular network/system aware of its distributed parts, which can be easily extended by non-technical users—"run this app and extend the network."
- Integration of advances in Artificial Intelligence (AI) and automated Machine Learning (ML) into information work-flows to deliver new possibilities to users in understanding complex data patterns and relationships within large data volumes and diverse data streams.
- The development of marine observing networks will increasingly be driven by the need to provide decision making information on government and economic matters. The emergence of large arrays of unmanned vehicles that are nimble in deployment, maintenance and low in cost will present unprecedented data coverage.
- Business models that allow manufacturers and commercial partners to use sensor-level standards, enabling users to easily retrieve and understand information directly from sensors. This will help build the foundation for new SMART data flows.
- When of interest to a non-specialist community (decision makers, the public at large), data products will increasingly be accessed from a remote cloud-based software process. Application functionalities will multiply as software (including APIs) becomes multi-platform and accessible by anyone, from anywhere (e.g., selectable from any device, service, and application, from smart devices to virtual research environments). Software development companies are likely to

[31] https://moses.geomar.de/de
[32] www.igmets.net
[33] http://www.emodnet-physics.eu/Map/platinfo/piroosplot.aspx?platformid=8805&7days=true
[34] https://doi.pangaea.de/10.1594/PANGAEA.883072

show interest in this usage, and as a result, user requirements will become key in the process of designing and developing new, more user-oriented, software.

- Development and implementation of standards for the securing and hardening of communication protocols (cyber-security) for robust platform communication, from sensor through to publication, as a means to ensure and document data provenance and traceability and to build trust in the source data.
- Full transparency for data use and uptake so that data providers will be able to readily determine the impact of their open datasets through cited reference searches within the academic literature, data download statistics and metrics and data service use when added to operational models. Such metrics will help build the case for sustained funding of observation networks and enable engagement with the full user community of a dataset.

RECOMMENDATIONS

The value of ocean data is in their uptake and use and in the subsequent value they add to individuals, organizations, Governments and custodians. This paper recommends the development of new data frameworks, information flows and knowledge pathways to deliver the understanding required to sustain, manage and protect our oceans. In particular the paper recommends the following actions and outcomes:

Sharing of Data Standards and Best Practices

The development of open source testing suits and benchmarking tools which allow for developing new data workflows, operationalizing standards, and publishing best practice. This development needs to be in partnership with commercial sensor manufacturers to increase uptake. Such tools will need to use the concept of data brokers and federating services to facilitate data interoperability and bring together the various providers (including commercial and user communities). An example of such a set-up would be an end to end federated network of quality control services.

Data Services

To move beyond data portals to service-based architectures that combine data provenance, persistence and security (both physical and cyber). These architectures should empower communities to develop services that serve their specific needs while maintaining data interoperability by utilizing the idea of data brokers and federated services. A demonstrator to show end to end data and information delivery via web services, as a direct replacement for a portal style of access, should be used as a means of educating the marine community around service-based architectures.

Sustainability of Infrastructure and Services

Standards, platforms and data services that have been adopted by scientific communities should be supported through the fostering of active support groups. With active engagement of the communities that depend on these tools, the burden of support, documentation and user engagement can be shared to reduce the overhead on a single entity. Stovepipes of brilliance should be exposed and celebrated through this mechanism of community embracement, instead of being punished through additional documentation and support requirements during the process of adoption beyond their original user community.

Data Standards and Best Practices

Continue the work on standards including the rationalization of standards and best practices, identifying gaps, and links between standards and best practices. Recognition of the need for standard persistent identifiers for sensors, data sets, models, and products. Implement governance arrangements, facilitate an interaction with the commercial sector, and work to bring new technologies and frameworks (such as the IoT and mid-level TRL technologies) into the standards process. Continue efforts toward building and disseminating ideas around best practice and the FAIR principles for data access and use.

End User Engagement

To deeply engage with a range of end users, including the commercial sector (including data companies such as Google, Microsoft and Amazon, instrument manufacturers and commercial information users such as the marine consulting industry) to understand their needs, to engage with them as potential solution providers and to partner with the larger data and informatics community around projects of common interest.

Engagement With International Web and Standards Organizations

To engage with international web and standards organizations (Microsoft, Google, data aggregators, Open Geospatial Consortium, World Wide Web Consortium, etc.) at the international coordination level (IODE/IOC/GOOS/WMO). This would enable alignment of IT infrastructure, standards and best practices beyond the marine and scientific domains, the sharing of expertise specific to environmental (ocean) data, and enable philanthropic exposure of data including reaching out to new users.

CLOSE

The coming decade will see increased pressure on the world's oceans and the systems they sustain as the impacts of climate change and other pressures, such as overfishing, pollution and coastal development, come to bear. Responding to threats such as the predicted increase in frequency and impact of coastal storms, the impact of rising sea levels, of increased frequency of coral bleaching and the mostly unknown impacts of ocean acidification, will require not only new data but new ways of delivery quality actionable information and ultimately the knowledge required to make sound decisions. While the threats to our oceans are increasing, so is the technology to capture and store data, to process data into information, and to contextualize and deliver this as knowledge.

This paper has articulated the types of frameworks, standards, systems and processes required to move beyond portals to truly democratize ocean data, contextualized by measures of data quality and security, to deliver the information and knowledge required to manage our oceans into the future. The decadal challenge is to build these systems, along with the governance, business and political environments that sustains them, to deliver the required knowledge to sustain and protect our oceans.

AUTHOR CONTRIBUTIONS

This paper is a collaborative effort by all co-authors. The paper structure along with Introduction, Vision for the future, Recommendations, and Close where produced collaboratively by the full authorship of this paper. Other sections were primarily produced and led by sub-teams within the author list. Democratization of data was primarily produced by SB, EB, and ED. User Trust—Data integrity and security was primarily produced by EB, MC, KC, and RH. Enabling technologies was primarily produced by JB, EB, JD, ED, JP, AK, LD, SJ, TG, and PB. End user engagement was primarily produced by ACK, KM, PF, ML, PB, and IS. The production of the paper was coordinated by JB and JP.

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The Ocean Observatories Initiative

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The Ocean Observatories Initiative (OOI) is an integrated network that enables scientific investigation of interlinked physical, chemical, biological and geological processes throughout the global ocean. With near real-time data delivery via a common Cyberinfrastructure, the OOI instruments two contrasting ocean systems at three scales. The Regional Cabled Array instruments a tectonic plate and overlying ocean in the northeast Pacific, providing a permanent electro-optical cable connecting multiple seafloor nodes that provide high power and bandwidth to seafloor sensors and moorings with instrumented wire crawlers, all with speed-of-light interactive capabilities. Coastal arrays include the Pioneer Array, a relocatable system currently quantifying the New England shelf-break front, and the Endurance Array, a fixed system off Washington and Oregon with connections to the Regional Cabled Array. The Global Arrays host deep-ocean moorings and gliders to provide interdisciplinary measurements of the water column, mesoscale variability, and air-sea fluxes at critical high latitude locations. The OOI has unique aspects relevant to the international ocean observing community. The OOI uses common sensor types, verification protocols, and data formats across multiple platform types in diverse oceanographic regimes. OOI observing is sustained, with initial deployment in 2013 and 25 years of operation planned. The OOI is distributed among sites selected for scientific relevance based on community input and linked by important oceanographic processes. Scientific highlights include real-time observations of a submarine volcanic eruption, time-series observations of methane bubble plumes from Southern Hydrate Ridge off Oregon, observations of anomalous low-salinity pulses off Oregon, discovery of new mechanisms for intrusions of the Gulf Stream onto the shelf in the Middle Atlantic Bight, documentation of deep winter convection in the Irminger Sea, and observations of extreme surface forcing at the most southerly surface mooring in the world ocean.

Keywords: ocean observing, marine geology and geophysics, physical oceanography, biological oceanography, chemical oceanography, ocean engineering

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INTRODUCTION

Overview

The Ocean Observatories Initiative (OOI) is a distributed, integrated network designed to enable next-generation scientific investigations of the complex, interlinked physical, chemical, biological, and geological processes that operate throughout the global ocean (ORION Executive Steering Committee, 2005, 2007). Since inception, the OOI has been a community-driven effort that continually incorporates and adapts state-of-the-art technology, with a goal of answering fundamental questions in Ocean and Earth Sciences, and contributing vital information to societally important activities, including fisheries management, maritime shipping, public safety, homeland security, hazards, and weather and climate forecasting. The OOI arrays (**Figure 1**), supported by documented procedures and metadata, and distributed to users in real-time via a common Cyberinfrastructure, address important questions at global, regional and local scales.

The Regional Cabled Array instruments a tectonic plate and overlying ocean at key locations in the northeast Pacific off Oregon, providing a permanent electro-optical cable connecting multiple seafloor nodes that provide high power and bandwidth for sensors from the seafloor to the ocean surface (Kelley et al., 2016). This system, which brings high-power and high- bandwidth real-time, two-way communications into the oceans with adaptive sampling capabilities, will continue to provide new insights into interlinked seismic, volcanic, and hydrothermal processes operating off the Oregon coast, the flux of methane from the seafloor, and the seafloor biosphere. The cabled moorings, which include instrumented wire crawlers and winched profilers, and associated seafloor instrumentation provide high-resolution temporal measurements of blue water and coastal ocean dynamics and ecosystems (e.g., hypoxia, thin layers, plumes, upwelling), biogeochemical interactions, and turbulent mixing.

The Coastal Arrays include the Endurance Array, a fixed system with connections to the Cabled Array, located off Washington and Oregon, and the Pioneer Array, a relocatable system with approximately 5 years planned at a series of locations to be selected by the National Science Foundation. The Endurance Array includes moorings and gliders to observe the coastal upwelling region of the Oregon and Washington coasts, and provides synoptic, multi-scale observations of the eastern boundary current regime, focusing on shelf-slope and air-sea exchange, carbon cycling, and acidification. The Pioneer Array currently occupies the New England shelf break, where moorings, gliders and propeller-driven underwater vehicles (e.g., Nicholson and Healey, 2008) are quantifying shelf-slope exchange and related interdisciplinary processes near the persistent shelf-slope front, which drive some of the nation's most productive ecosystems.

The Global Arrays consist of deep ocean moorings (e.g., Weller et al., 2012) and buoyancy-driven ocean gliders (Rudnick et al., 2004) that provide interdisciplinary measurements of the water column, mesoscale variability, and air-sea fluxes at critical locations worldwide. Locations include the Irminger Sea off Greenland, a site of the deep-water formation that forms part of the Atlantic meridional overturning circulation, a key component of the climate system; Station Papa in the Northeast Pacific, a site of longstanding interdisciplinary interest; the Argentine Basin, a highly biologically productive, energetic, data-sparse region; and the Southern Ocean off Chile, seen as central to the global carbon cycle and global heat and energy budgets (National Academies of Sciences, Engineering and Medicine, 2015).

The OOI CI is based on the uFrame™ software, developed by Raytheon, Inc., and adapted and extended for OOI use. The uFrame-based system parses and processes raw data and presents it in response to user queries, made over the Internet through the CI web-based portal access point. A machine-to-machine (M2M) interface provides programmatic access to a Program network, termed OOINet, through a representational state transfer (RESTful) application programming interface (API). M2M supports an alternative ERDDAP data delivery solution. The CI system uses a life-cycle management architecture that integrates a redundant enterprise storage area network (disk-based) and a robotic library (tape-based), with redundancy implemented at different layers. The CI software system uses a service-oriented architecture (AOA) and implements dataset drivers, cabled instrument and platform drivers, and data product algorithms to produce data products on demand. The OOI CI system implements a multi-tier security approach, supporting traffic encryption, network traffic segregation, multi-layer traffic filtering, multi-layer access control, and monitoring.

The OOI was designed to provide a unified approach to the comprehensive investigation of themes central to Ocean and Earth Science (ORION Executive Steering Committee, 2005): (1) ocean-atmosphere exchange; (2) climate variability, ocean circulation, and ecosystems; (3) turbulent mixing and biophysical interactions; (4) coastal ocean dynamics and ecosystems; (5) fluid-rock interactions and the subseafloor biosphere; and (6) plate-scale, ocean geodynamics.

As a science-driven ocean observing program, the OOI is related to but distinct from the Integrated Ocean Observing System (IOOS), which has the mission of producing and communicating information that meets the safety, economic, and stewardship needs of the United States (e.g., Rayner, 2010). The OOI Coastal Pioneer Array complements the nearby IOOS arrays maintained by the Northeastern Association of Coastal Ocean Observing Systems (NERACOOS) and the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS). Similarly, the OOI Regional Cabled Array and the OOI Coastal Endurance Array complement the nearby IOOS array maintained by the Northwest Association of Networked Ocean Observing Systems (NANOOS).

Elements of OOI History

After extensive planning, advocacy, and collaboration by community leaders in the 1990s, the National Science Board in 2000 approved the OOI (then called ORION) as a potential Major Research Equipment and Facilities Construction project for possible incorporation in a National Science Foundation (NSF) budget. The NSF established the OOI Project Office in 2004 and an Executive Steering Committee in 2005 to coordinate further planning.

In 2005, the OOI Project Office issued a Request for Assistance, resulting in submission of 48 proposals, which were peer reviewed. NSF Advisory Committees used the proposals and reviews to develop the Conceptual Network Design, which was presented at a community-wide Design and Implementation Workshop in 2006. In 2006, the NSF assembled a Science Panel,

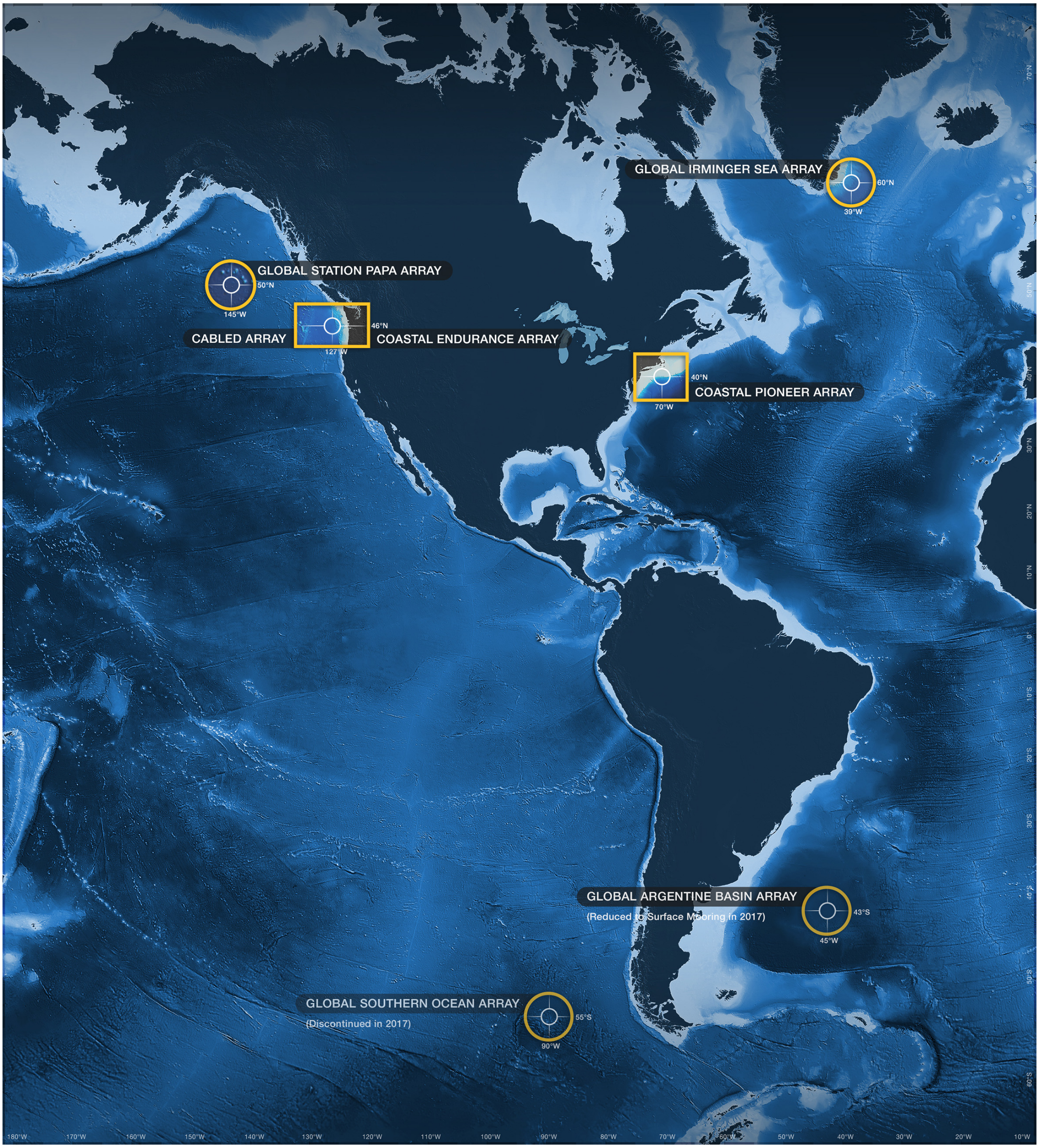

FIGURE 1 | OOI Arrays. Figure credit: Center for Environmental Visualization, UW School of Oceanography.

which reviewed and endorsed the Conceptual Network Design, and a Conceptual Design Review, which endorsed the feasibility, budget, and plans.

In 2007, through competitive peer-reviewed processes, the NSF selected the University of Washington (UW) as the Implementing Organization (IO) for the Regional Cabled Array, the University of California San Diego (UCSD) as the IO for the Cyberinfrastructure, and the Woods Hole Oceanographic Institution (WHOI), in partnership with the Scripps Institution of Oceanography (SIO) and Oregon State University (OSU), as the IO for the Coastal and Global Scale Nodes, consisting of the Coastal Endurance and Pioneer Arrays and the Global

Arrays. The Consortium for Ocean Leadership (COL) hosted the Project Management Office. NSF held Preliminary and Final Design Reviews in 2007 and 2008, resulting in acceptance of the OOI Final Network Design and a recommendation to proceed with construction. The NSF held a Cost and Schedule Review and a Science Review Panel in 2009. Following authorization by the National Science Board, the NSF in 2009 established a Cooperative Agreement with COL to initiate funding for design and construction, and COL established subawards to the IOs.

Design commenced in 2009, and the subsequent construction, installation, testing, and validation culminated in commissioning of the OOI arrays in 2016, followed by initial operation. During design and construction, OSU became a separate IO responsible for the coastal Endurance Array, SIO withdrew from the Coastal and Global Scale Nodes, and the Cyberinfrastructure transitioned first to SIO and then, using an alternative technological approach, to Rutgers University. In 2017, because of budget constraints, the Global Array in the Argentine Basin was discontinued, although data collected at this site continues to be served through the OOI Cyberinfrastructure, and the Global Array in the Southern Ocean was reduced in scope, although continued under joint funding from the NSF through the OOI and from the United Kingdom.

In 2016, the NSF issued a solicitation for operation and management of a five-year continuation of the OOI, termed OOI 2.0, with an option to renew. The NSF reviewed and evaluated the proposals and submitted status and plans to the National Science Board, which in 2018 approved allocation of funds to the continuation of the OOI. The NSF established a Cooperative Agreement with WHOI, which in turn established Cooperative Agreements with partners UW, OSU, and Rutgers. WHOI hosts the Program Management Office and is responsible for the Coastal Pioneer and Global Arrays. UW, OSU, and Rutgers are responsible for the Regional Cabled Array, Coastal Endurance Array, and Cyberinfrastructure, respectively. OOI 2.0 commenced in October 2018.

Scope of This Article

The following describes science drivers, infrastructure, and science highlights for the Regional Cabled Array (Section "Regional Cabled Array"), the Coastal Endurance and Pioneer Arrays (Sections "Coastal Endurance Array" and "Coastal Pioneer Array"), and the Global Arrays (Section "Global Arrays"). Section "The Future" addresses the future. The Cyberinfrastructure is described elsewhere (Rodero Castro and Parashar, 2016, 2019; Zamani et al., 2017).

REGIONAL CABLED ARRAY

Science Drivers

The network design for the high-power and -bandwidth Regional Cabled Array (RCA, **Figures 1**, **2**) is based on the premise that many globally significant processes, which operate beneath/at the seafloor and throughout the overlying water column, are expressed at or below a regional scale (Regional Cabled Observatory Network (of Networks) [RECONN], 2004). Hence, the implemented RCA extends > 500 km across the Juan de Fuca Plate spanning coastal to blue water environments and from the Cascadia Margin to the Juan de Fuca mid-ocean ridge spreading center. The extended spatial coverage of the RCA, real-time two-way communication capabilities, 24/7 measurements over decades, and sampling periods from microseconds to minutes provide unparalleled capacity to examine in both space and time processes at the scales at which they are operating and interacting with a representative suite of natural phenomena that occur throughout the world's ocean. The key site locations and science drivers for the RCA were honed from sixteen proposals involving > 175 scientists that responded to the NSF's Request for Assistance in 2005. Primary science drivers and detailed rational for the RCA are described in the RECONN report (Regional Cabled Observatory Network (of Networks) [RECONN], 2004) and in the OOI Science Prospectus (ORION Executive Steering Committee, 2005, 2007). Each RCA site, briefly described below, is located in a specific geographic region (**Figure 2**) to address the most science for the widest community.

The Slope Base – Cascadia Margin site is located ∼125 km east of Newport, Oregon (OR), adjacent to the continental slope at a water depth of approximately 2,900 m. Here, RCA geophysical sensors focus on detection of seismic and tsunami events associated with earthquakes along the Cascadia Subduction Zone and within the accretionary prism. Shallow Profiler and Deep Profiler moorings with a complementary set of seafloor sensors are directed at understanding processes associated with climate change, ocean and ecosystem dynamics, biogeochemical cycles, and topographic forcing effects in an area impacted by the eastern boundary California Current.

The Southern Hydrate Ridge site (780 m water depth) hosts abundant vigorously venting seeps that emit methane-rich fluids with bubble plumes reaching > 400 m above the seafloor, possibly supporting life in the upper water column (Philip et al., 2016). The seeps support dense colonies of methane-metabolizing microbes and animals with methane hydrogen sulfide utilizing symbionts (Suess, 2014). Science drivers include quantifying the flux of methane from the seafloor into the overlying ocean, critical to understanding carbon-cycle dynamics and the impacts of global warming on methane release. Other science drivers include understanding biogeochemical coupling, associated with gas hydrate formation and destruction, and linkages between seismic activity and methane release.

The Oregon Endurance Array Offshore and Shelf Sites include both uncabled and RCA infrastructure (**Figure 2**). This is a multi-scale array utilizing fixed and mobile assets to observe cross- and along-shelf variability in the coastal upwelling region off the OR coast, while simultaneously providing an extended spatial footprint that encompasses a prototypical eastern boundary current regime (the California Current). This integrated infrastructure bridges processes from the coastal zone (OR and Washington Endurance Arrays; Southern Hydrate Ridge) through their transition into the ocean basin interior (Slope Base and Axial Seamount). These sites are designed to examine biogeochemical and physical oceanographic processes within such highly productive coastal environments (see Section "Coastal Endurance Array"), specifically, the impacts

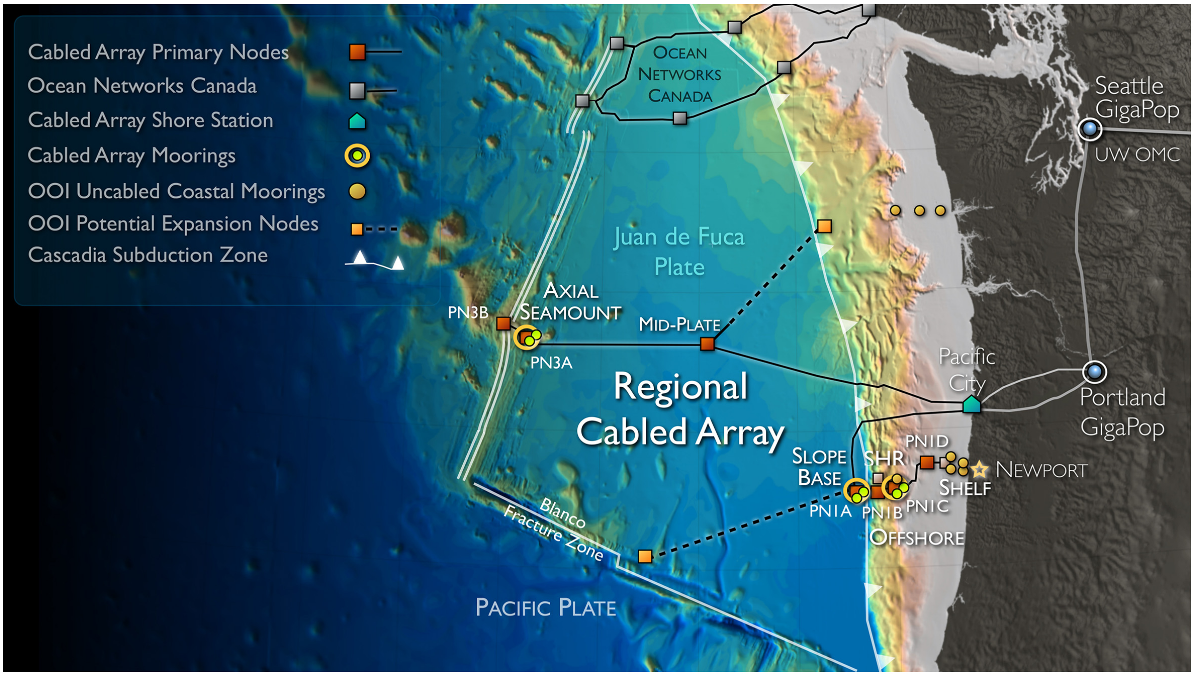

FIGURE 2 | Location of the Regional Cabled Array spanning the Cascadia Margin and Juan de Fuca Plate. Coupled Shallow Profiler and Deep Profiler Moorings are located at the Slope Base, Oregon Endurance Offshore and Axial Base sites. Location of Primary Nodes (PN1B–PN3B and the mid-plate site (PN5A) are shown connected to the backbone cable. Potential expansion capabilities include the Blanco Fracture Zone and sites off of Grays Harbor, WA. Figure credit: Center for Environmental Visualization, UW School of Oceanography.

of wind-driven upwelling of nutrient-rich currents on biological communities and hypoxia events.

The Axial Seamount site is located far from the continental shelf (>350 km) and hence represents an open-ocean or pelagic site in the continuum of observing scales represented in the RCA system (**Figures 2**, **3**; Kelley et al., 2014). Here, large-scale currents including the North Pacific Current, the subpolar gyre and the northern end of the California Current interact. These currents transport heat, salt, oxygen, and biota, all of which are crucial to the region's ecosystem. The currents' variability arises from forcing with timescales as varied as tide and winds to interannual (El Niño) and decadal (Pacific Decadal Oscillation) processes. Science themes focused on Axial Base include: (1) How, and how strongly do tidal currents break down into turbulence, and what are the feedbacks on the large scale current system? (2) What is the impact of long- and short-term forcing changes on the structure and transports of the large-scale current system? and (3) What are their effects on the ecosystem? Additional focus is on monitoring plate scale seismicity and local earthquakes associated with magma migration within the volcano, as well as spreading events along the Juan de Fuca Ridge and far-field earthquakes.

The Axial Caldera site is the most advanced underwater volcanic observatory in the worlds' oceans (**Figures 2**, **3**; Kelley et al., 2014, 2016). The submarine volcano, located ~500 km off the OR coast, is the most magmatically robust volcano on the Juan de Fuca Ridge (**Figure 2**). A diverse seafloor instrument array at the summit of the volcano focuses on better understanding of crustal formation processes, including diking-eruptive events; relationships between seismic activity and fluid flow in diffuse and black smoker sites; and how changes in fluid temperature and chemistry impacts microbial and macrofaunal communities. Here, formation of snowblowers associated with diking eruptive events provides insights into the deep biosphere.

Infrastructure

The submarine network includes two high power (8 kW) and bandwidth (10 Gb/s) telecommunication fiber-optic subsea cables extending westward from a Shore Station in Pacific City, OR (**Figure 2**). The northern branch extends ~480 km across the Juan de Fuca Plate to Axial Seamount. The second branch runs parallel to the northern branch initially, but extends southward 208 km along the base of the Cascadia Subduction Zone (2900 m water depth) and then eastward 147 km to 80 m water depth offshore of Newport, Oregon. The RCA is composed of (1) Primary Infrastructure that includes the Shore Station, ~900 km of submarine backbone fiber optic cables, and seven Primary Nodes; and (2) the Secondary Infrastructure that includes 33 km of extension cables, 18 junction boxes, 6 moorings, and more than 140 cabled instruments.

Primary Infrastructure

The Shore Station is the terrestrial termination facility for the RCA system (**Figure 2**). A suite of high-voltage components provides 10 kV DC output for transmission to the undersea cables and nodes. Network management systems allow controlled

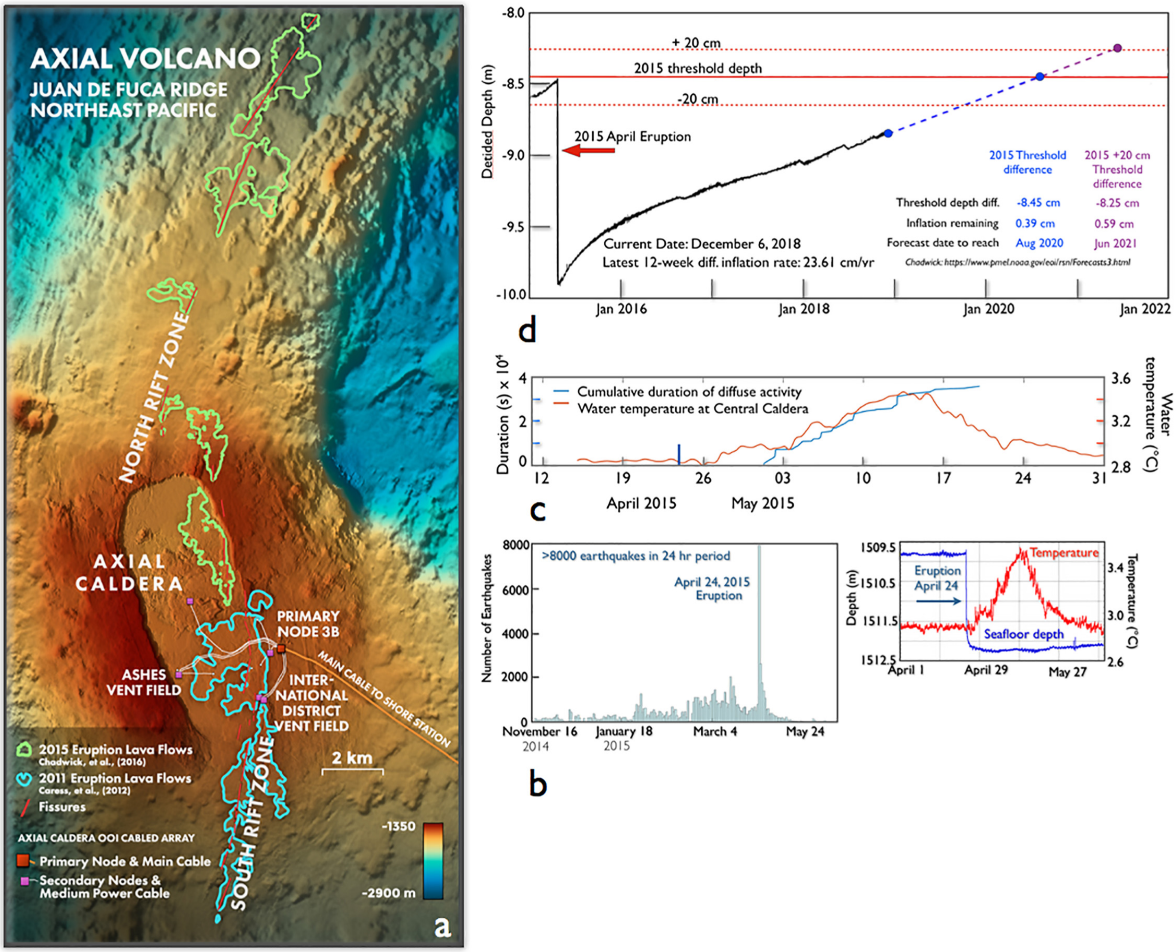

FIGURE 3 | (a) Summit and flanks of Axial Seamount showing location of the 2011 and 2015 eruptions in relation to the RCA infrastructure installed in 2014. Figure credit: Center for Environmental Visualization, UW School of Oceanography. **(b)** Left – Number of earthquakes each day as streamed to shore live by RCA short-period seismometers and the initiation of the April 24, 2015 eruptive event (after Wilcock et al., 2016). Right – Coincident deflation of the seafloor measured by cabled bottom pressure-tilt instruments and increase in water temperatures (https://www.pmel.noaa.gov/eoi/rsn/24April2015_event.html; after Xu et al., 2018). **(c)** Diffusive (10–100 Hz) hydrophone signals indicative of explosive events and increase in water temperatures in the caldera following (after Caplan-Auerbach et al., 2018). **(dx)** Daily forecast of eruptive threshold by W. Chadwick based on detided data from the cabled bottom pressure-tilt instruments.

allocation of resources across the network (e.g., power) and real-time monitoring of communication and power systems for activity, status, utilization, and alarms. The systems also receive and aggregate streaming science data from the Primary Nodes. Three redundant high-bandwidth terrestrial telecommunication backhaul cables provide connectivity from the Shore Station to the Pacific Northwest Gigapop (PNWGP), Seattle, WA. The PNWGP Internet network provides transfer of RCA data to the OOI Cyberinfrastructure at Rutgers University and to the UW Operations Center.

The two northern and southern submarine Backbone Cables provide power and redundant communication to each Primary Node, which are distribution centers for extension cables that provide direct access to the specific sites of scientific interest. Each Primary Node provides 8 kW of total power, 10 GbE bandwidth, and pulse per second (PPS) timing. Five science ports (1 GbE, 375 V), two high- bandwidth science ports (10 GbE, 375 V), and two backbone expansion ports (10 kV) on each node provide power and communication to the secondary junction boxes.

Secondary Infrastructure

Key observational sites are accessed by the Secondary Infrastructure, which includes 33 km of extension cables, 18 low- and medium-power junction boxes and low-voltage nodes, three instrumented Shallow Profiler Moorings, three instrumented Deep Profiler Moorings, and 140 instruments of >30 types.

To access specific experimental sites, low- to medium-power and low-voltage Junction Boxes (Secondary Nodes), designed and built by the UW Applied Physics Laboratory (APL), are connected to the Primary Nodes by extension cables that can reach up to ~5 km in length. Each junction box includes eight configurable instrument ports, and all 18 have been fully operational since installation in 2014.

Pairs of Deep Profiler and Shallow Profiler Moorings are located at Slope Base (2900 m), on the Oregon Margin at the Endurance Offshore (600 m), and at the base of Axial Seamount (2600 m). The moorings includereal-time command and control, and are designed to measure global and local currents, megaplumes, ocean chemistry (e.g., pH, CO_2, nutrients), heat flux, thin layers, and biological parameters (e.g., zooplankton times series distribution and chlorophyll).

The Deep Profiler mooring is a single cabled, vertical mooring that hosts an instrumented McLane wire-following vehicle that measures ocean properties from ~10 m above the seafloor to ~ 150 m water depth. A basal docking station provides inductive charging for the vehicle battery and inductive communications during profiling. While in the dock, a Wi-Fi antenna provides high-speed download of stored profiler datasets from the vehicle, with data transmission to shore via the cabled network.

The state-of-the-art cabled Shallow Profiler Mooring is a two-legged mooring built by the UW APL (McRae, 2016). The mooring includes a 3.66 m wide and 7,000-lb platform situated at ~200 m water depth. Each platform, which receives up to 3 kW power, hosts a stationary, instrumented Platform Interface Assembly and a winched Science Pod that traverses the upper ~200 m water column to ~5 m beneath the oceans' surface, depending on wave conditions. Real-time two-way communication capabilities of the Cabled Array interface with an array of 15 to 18 science instruments. The operating system provides command and control capabilities that include implementation and switching of predefined missions, and changing of mission parameters "on the fly" with commands from the UW Operations Center. Current profiler missions include 9 round-trip profiles/day through the water column with automated stops at specific depths on the downcast of two of them to allow the profiler pod to stop at specific depths and turning of instruments on and off that require stationary measurements (e.g., pCO_2). Engineering and science data are streamed back live to shore and the profilers have conducted >30,000 profiles since 2015. Significant expansion capabilities are also built into the mooring assembly for addition of new technologies (e.g., flow cytometers, 3D imagers, DNA analyzers). In concert, the instrument and platform capabilities allow high temporal and spatial measurements (e.g., upcast at 5 cm/s) to be made that were never before possible. Because of shore-based mission control, instruments on the winched Science Pod are particularly well suited to examine, in real-time, biologically rich thin layers 1–2 m thick or less, stemming from small scale chemical or hydrodynamic gradients. A complementary set of instruments near the seafloor address hypoxia, tsunami, and seismic events; internal tides; and flow of currents onto the shelf.

In addition to the water column instruments on the moorings and near the seafloor, an interdisciplinary suite of seafloor instruments is focused on geophysical, biogeochemical, and physical processes associated with deformation along the subduction zone margin, and at Axial Seamount, crustal formation, hydrothermal vents, and methane seeps. Geophysical instruments are located at Slope Base, Southern Hydrate Ridge, Axial Base, and at the summit of Axial Seamount. Many of the geophysical-biogeochemical-physical instruments are novel to the RCA, including *in situ* mass spectrometers, pore-fluid flow meters, hydrothermal fluid and particulate DNA samplers, bottom pressure-tilt instruments, and a temperature-resistivity instrument and pH-H_2S-temperature instrument located in >300°C chimney orifices.

Science Highlights

In 2016, NSF announced opportunities for proposals to use OOI data and to add instrumentation onto the OOI arrays. A key outcome of this was that numerous awards were made to non-OOI Principal Investigators (PIs) to add instrumentation onto the RCA, facilitated by the systems significant built-in expansion capabilities and real-time command and control and data flow. New awards were distributed among multiple funding agencies that included the NSF, Office of Naval Research, NASA, and an international award from Germany. PI instrument awards included the addition to the RCA of two instruments that provide high resolution drift-corrected pressure measurements for geodynamic studies on volcanoes and subduction zones; a short baseline flipping tilt meter for deformation studies at Axial, with follow-on applications for detecting slow slip events; sonars for quantifying hydrothermal plumes and bubble plumes emanating from methane seeps and associated changes in seafloor geomorphology; and energy extraction from hydrothermal vents.

Several NSF OOI data-use awards were made also made for numerous RCA data projects focused on Axial Seamount, with emphasis on the 2015 eruption. Results from these studies provide unprecedented insights into the eruptive evolution of this highly active volcano and have led to the first predictive models of when a submarine eruption will occur (**Figure 3**) (Nooner and Chadwick, 2016). On April 24, 2015 the cabled network captured live the eruption of Axial. Over an ~24 h period >8,000 earthquakes were recorded (Wilcock et al., 2016) and the seafloor fell by >2 m (Nooner and Chadwick, 2016). Several lava flows erupted on the Northern Rift, one of which reached 127 m in thickness (Kelley et al., 2014; Chadwick et al., 2016). Over 37,000 water-born impulsive events, consistent with underwater explosions, were recorded spatially associated with the lava flows (Wilcock et al., 2016). Explosions near the northern flows continued until May 21, coincident with when the caldera started inflating again (Wilcock et al., 2016). Diffuse, prolonged broadband signals over four distinct time periods starting April 24 and lasting ~2 min to 1 h duration are interpreted to reflect explosive degassing and production of ash material similar to explosive volcanism observed in Hawaii (Caplan-Auerbach et al., 2018); ash was also observed on RCA instruments in the central portion of the caldera. Some of the diffuse signals were coincident with an 0.6–0.7°C increase in water temperatures across the southern half of the caldera, which may reflect the release of warm dense brines previously stored in the crust (Xu et al., 2018) through phase segregation processes associated with boiling and supercritical phase separation (Butterfield et al., 1990; Kelley et al., 2002). Warm circulation of fluids within and out of the northern flows, elevated in methane and hydrogen, formed snow blowers and near seafloor plumes with microbiologically distinct communities (Spietz et al., 2018).

Real-time data from the RCA bottom pressure-tilt instruments at Axial are currently incorporated into inflation models for forecasting when thresholds will may be reached for a new eruption, based on the three prior eruptive events (Chadwick[1]).

COASTAL ENDURANCE ARRAY

Science Drivers

As far back as 2003, a research-driven coastal observatory was visualized as a long-term Endurance Array and a relocatable Pioneer Array (Jahnke et al., 2003). The Endurance Array would provide continuous observations at key locations, documenting episodic events and longer-term changes and would complement existing and planned regional observations. The Pioneer Array (Section "Coastal Pioneer Array") in turn would provide higher resolution for process studies.

The OOI Endurance Array proposed and funded from these early concepts is located off the coasts of Oregon and Washington in an archetypal coastal upwelling system. Its location, platforms and sensors were designed to address the major OOI Science Themes of Ocean-Atmosphere Exchange, Ocean Circulation, Mixing and Ecosystems, Climate Variability and Ecosystems, and Coastal Ocean Dynamics and Ecosystems with a particular focus on Hypoxia on Continental Shelves and Shelf/Slope Exchange (ORION Executive Steering Committee, 2007).

Physically, the coastal ocean off Oregon and Washington is characterized by a relatively narrow shelf, wind-driven upwelling and downwelling, and buoyancy forcing from regional rivers including the Columbia River, the largest source of freshwater to the US west coast. Regional mesoscale variability is forced by bathymetry, fluid dynamical instabilities and coastally trapped waves. At the largest scales, interannual variability is forced by fluctuations in the tropical Pacific (e.g., El Niño Southern Oscillation), as well as variations in the large-scale circulation of the North Pacific (e.g., Pacific Decadal Oscillation).

The chemical and biological variability of the regional ecosystem is embedded within the larger California Current Ecosystem (Mackas, 2006). Oregon and Washington coastal waters are home to a diverse range of fisheries that rely on the injection of nutrients into the euphotic zone by upwelling and the subsequent blooms of phytoplankton that form the base of the oceanic food web. The amount and timing of the spring-summer upwelling season is crucial to the regional ecosystem. At longer time scales, interannual variability can drive ecosystem variability such as swings between northern, "fatty" zooplankton and southern, "skinny" zooplankton (Peterson and Schwing, 2003).

In recent years, hypoxic and even anoxic events have regularly occurred off Washington and Oregon as they have in upwelling regions worldwide (Grantham et al., 2004; Chan et al., 2008). During these same years, the threat of Ocean Acidification to marine organisms in this area and across the California Current Ecosystem has become very clear (Feely et al., 2008; Barton et al., 2012; Klinger et al., 2017). While a known threat to ocean and human health, harmful algal blooms in this region (Trainer et al., 2009) were particularly severe during recent years with the upper-ocean warming introduced by the "Warm Blob" (McCabe et al., 2016; McKibben et al., 2017).

Within the coastal ocean, physical processes, water properties and biological community size and composition vary most strongly in the cross-shelf direction. A well-instrumented array spanning the continental shelf is key to sorting out physical and ecosystem response across this strong gradient. Shelf stratification and upper-ocean properties differ north and south of the Columbia River, so observations along both lines are needed to understand coastal ocean ecosystem responses. The whole system shows strong, linked variability from diurnal to synoptic, seasonal and interannual time scales. The observational requirements that ocean properties from physics, to chemistry to biology be measured on many different time and space scales drive the design of the Endurance Array infrastructure.

Infrastructure

The Endurance moored array includes the Oregon Line, off Newport near 44.6°N, and the Washington Line, off Grays Harbor near 47°N (**Figure 4**). These lines each have three sites. One at the inner shelf (∼25–30 m water depth, 4–6 km from shore, "Inshore"), the "Shelf" (∼80–90 m depth, 20–30 km from shore), and the continental slope (∼500–600 m depth, 60–65 km from shore, "Offshore"). These cross-shelf locations were chosen to sample distinct dynamical regions: the inner shelf where wind, waves and river plumes all influence the circulation and stratification, and where the ocean connects to the sandy shores and rocky intertidal reefs; the shelf where upwelling fronts, alongshore jets and plankton blooms are found, and where the bottom is muddy and near-bottom hypoxia has been observed to peak; and the continental slope where a subsurface, poleward undercurrent exists, zooplankton migrate from a few hundred meters to the surface each day and night, and wind-stress curl and offshore eddies interact with the coastal circulation.

The Endurance Array shares platform types found across the OOI. Each Endurance Array site includes a surface buoy with measurements, profiling water column measurements and near bottom measurements. On the Oregon line, the Endurance Array near-bottom and water column instruments are operated and maintained as part of the Regional Cabled Array (Section "Regional Cabled Array"). Glider lines connect the Endurance Array sites in the cross-shelf direction and provide some measure of along-shelf resolution.

The Endurance Array employs three types of surface moorings, the coastal surface mooring (CSM), inshore surface mooring, and coastal profiler mooring (CPM). At the shelf and offshore sites, CSMs such as the one shown in **Figure 5** support meteorological and oceanographic instruments on the buoy. Within the euphotic zone, there is a highly instrumented platform at 7-m depth. Physical, chemical and bio-optical measurements are made here. These buoys and their near surface frames are the same design used on the Pioneer Array (see discussion in Section "Coastal Pioneer Array"). At the Oregon shelf and offshore sites, the buoys are connected to an un-instrumented recovery frame at the bottom. For these sites, the near bottom observations are

[1] https://www.pmel.noaa.gov/eoi/rsn/

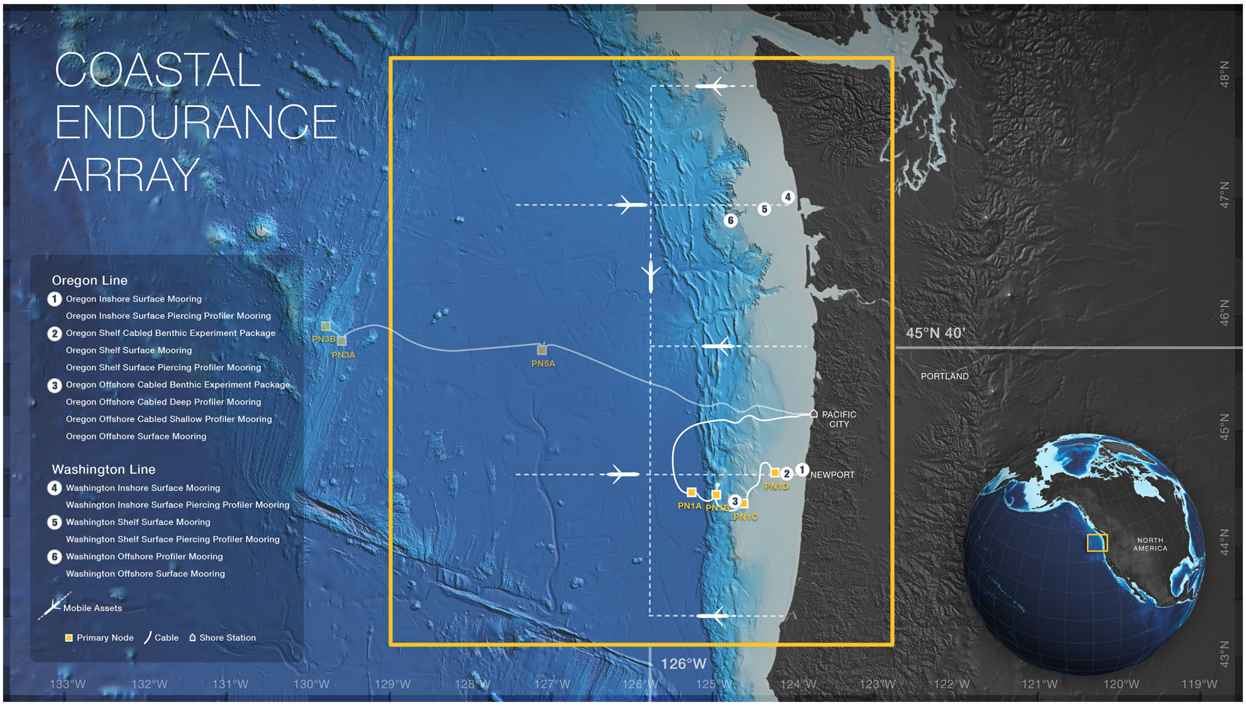

FIGURE 4 | The Endurance Array mooring locations (numbered dots) and glider track lines (dashed) are shown relative to the Pacific Northwest US continental shelf (gray) and slope (medium blue). The Endurance array mooring lines include the Washington Line sampling north of the Columbia River and the Oregon Line sampling south of the river. The Oregon line is tied in with the Regional Cabled Array at the Oregon shelf and offshore sites. Figure credit: Center for Environmental Visualization, UW School of Oceanography.

provided by the benthic experiment packages deployed as part of the RCA (**Figure 5** and Section "Regional Cabled Array"). At the Washington sites and at the Oregon inshore site, the surface moorings are connected to an instrumented multifunction node as at the Pioneer Array. This platform is similar to the bottom frame depicted below the surface mooring in **Figure 5**, but it is fully instrumented with near-real time reporting through the surface mooring. The cabled benthic experiment packages and instrumented multifunction nodes are designed to provide similar capabilities insofar as is possible.

The second type of surface mooring deployed on the Endurance Array is the inshore CSM. These moorings are designed to provide year round coverage at the Oregon and Washington inshore sites. Due to high wave events in winter, the inner-shelf has historically been a very difficult area to measure. Endurance inshore moorings meet this challenge using submersible surface buoys attached to the seafloor instrument package with a flexible mechanical and electrical element that can stretch up to two times its length. The moorings have a reduced set of measurements on the buoy itself, but have the same near surface and bottom platforms and instruments as other OOI CSMs.

All Endurance surface moorings are paired with a profiling mooring to link the surface and bottom fixed measurements. The Endurance Array has four types of profilers. All have self-contained instrument packages that move up and down through the water column and provide fine (0.25 m) vertical resolution at a fixed location. At the Oregon offshore site, the surface mooring is paired with the RCA Shallow and Deep Profiler Moorings (see Section "Regional Cabled Array"). These profilers use the high power and bandwidth capabilities of the RCA. Other Endurance sites are paired with uncabled profilers. At the Washington offshore site, the surface mooring is paired with the third surface mooring type on Endurance. The CPM supports an uncabled wire following profiler identical to those deployed on Pioneer (see Section "Coastal Pioneer Array"). These profilers carry low-power instruments measuring temperature, salinity, pressure, water velocity, light, chlorophyll fluorescence, light backscatter from particles, and dissolved oxygen.

The Endurance shelf and inshore sites off Oregon and Washington (four sites total) are paired with coastal surface piercing profilers (CSPP's) as shown in **Figure 5**. Endurance Array engineers and scientists worked with Sea-Bird Scientific's WET Labs to make the original autonomous coastal profiling concept (Barnard et al., 2010) more robust. The CSPP's measure from a few meters above the sea floor to the air-sea interface. Their capability to measure to the air-sea interface is unique among OOI profilers. CSPP instruments include nitrate, light attenuation and absorption, and spectral irradiance in addition those noted above. CSPP's are part of the year round sampling plan at the Oregon and Washington shelf sites. At the inshore sites, CSPP's are deployed between about April and September as the wave climate precludes deployment between October and March.

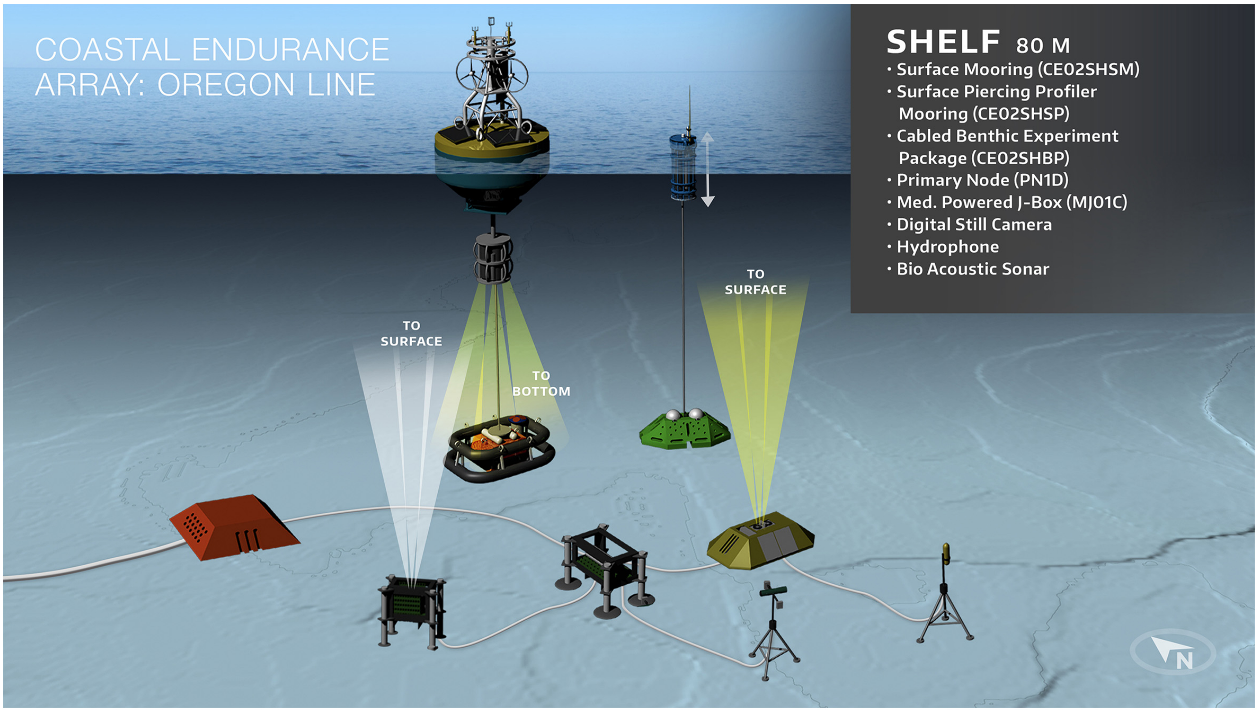

FIGURE 5 | Schematic of the Endurance Array Oregon Shelf site showing the platforms spanning from the air-sea interface to the seabed. The surface mooring includes buoy and near surface instrument frame sensors. The coastal surface piercing profiler provides high vertical resolution water column measurements. The Oregon Shelf and Offshore sites link the Regional Cabled Array (RCA) and the Endurance Array. The near-bottom sensors at this site are part of the RCA. While platform types vary across the Endurance Array, other sites provide analogous top to bottom coverage. Figure credit: Center for Environmental Visualization, UW School of Oceanography.

Underwater gliders provide the greatest geographic coverage, spanning about 500 km from northern Washington south to Coos Bay, Oregon (**Figure 4**). The two glider lines on the Endurance Array main mooring lines of Newport, Oregon, and Grays Harbor, Washington, run from the coast to 128°W, about 300 km. Gliders with 200-m buoyancy pumps sample the inshore parts of the cross-shelf lines weekly in order to capture wind-driven changes, while gliders equipped with 1000-m pumps sample the offshore parts of the lines less frequently to measure the more slowly varying deep ocean. Glider coverage is prioritized along the Washington and Oregon lines. The gliders sample the fine vertical structure of the ocean from the sea surface to within meters of the seafloor or up to 1000 m depth, whichever is deepest. Endurance coastal gliders have the same low-power sensors as those on Pioneer. Sensors consist of CTD, photosynthetically active radiation, oxygen, three-channel bio-optics (chl-a, CDOOM fluorescence and backscatter), and 600 kHz ADCP.

All the Endurance Array platforms and sites including profilers and gliders measure essential ocean variables such as temperature, salinity, pressure, water velocity, chlorophyll fluorescence, and dissolved oxygen. Instruments that require significant power, space and bandwidth are deployed as fixed instruments on the moorings. These instruments include the full suite of meteorological instruments on the buoys, and chemical, bio-optical and bio-acoustic instruments near the surface and at the bottom. A partial list of Endurance fixed depth measurements includes partial pressure of carbon dioxide, pH, nitrate, multi-spectral optical attenuation and absorption, spectral irradiance, three frequency acoustic backscatter, and digital still images. Together, the Endurance moored instruments monitor and characterize many elements of the local physics, chemistry, and biology.

The Endurance instrument sampling protocols are designed to satisfy science requirements for observing coastal ocean phenomena. On the surface moorings, all instruments collect at least one burst of data per hour and there additional evenly spaced bursts as there is power to support. A few instruments are limited by chemical reagents and a couple are limited by calibration drift. The uncabled Coastal Surface Piercing Profiler is designed so that its instruments can measure the water column with the same 0.25-m resolution as the underwater gliders; the CSPP's CTD measures every 1.5-cm with the goal to resolve "thin layers" of plankton.

Science Highlights

Here we focus on results pertinent to two Key Endurance science drivers, Climate Variability and Ecosystems, and Hypoxia on Continental Shelves. Henderikx Freitas et al. (2018) describe and contrast variability between the Washington and Oregon shelves using OOI and satellite data. Barth et al. (in press) use OOI data

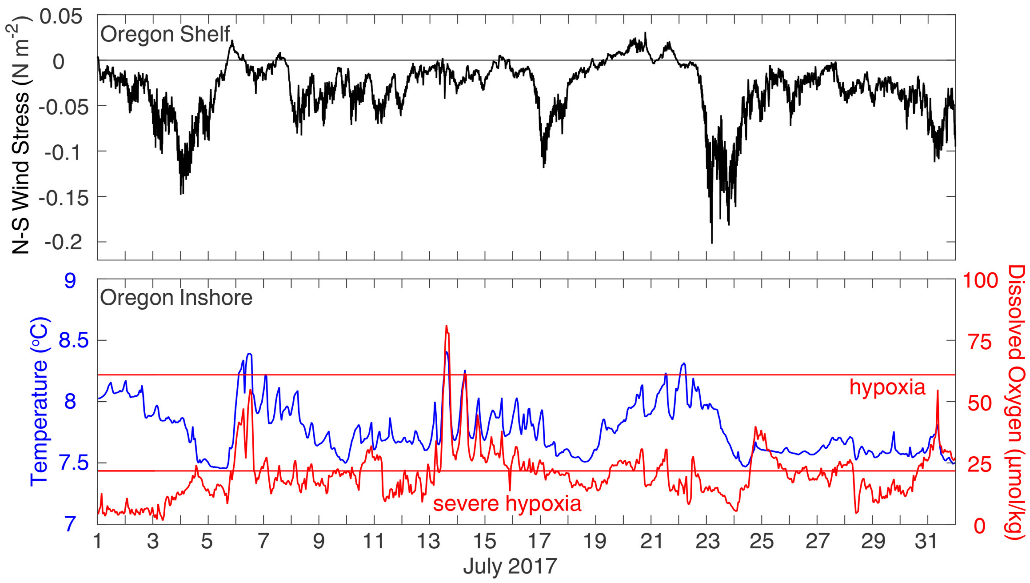

FIGURE 6 | Dissolved oxygen (µ Mol kg^{-1}, red) and temperature (°C, blue) from near the bottom at the 25-m OOI Oregon Inshore mooring, and north-south wind stress (N m^{-2}, black) from the OOI Oregon Shelf surface mooring. Levels of dissolved oxygen for hypoxia (~62 µ Mol kg^{-1}, 1.4 mL/L) and "severe" hypoxia (~22 µ Mol kg^{-1}, 0.5 mL/L) are indicated by horizontal red lines (Adapted from Barth et al., in press). Reproduced with permission from the Oceanography Society.

to describe short term changes in hypoxia over the Oregon inner shelf in response to wind forcing.

Henderikx Freitas et al. (2018) incorporate OOI mooring, and glider estimates of chlorophyll-a and chromophoric dissolved organic matter (CDOM) fluorescence over the Endurance Washington and Oregon lines to characterize seasonal patterns cross-shelf gradients in particle concentrations between the Washington and Oregon shelves. The Columbia River exerts a strong seasonal influence on the Washington shelf, but smaller coastal rivers and resuspension processes also appear important in determining particle distributions nearshore during winter. Glider chlorophyll fluorescence is similar in magnitude across the two shelves for the period examined. The *in situ* observations contrast with differences observed from satellite data, which show higher chlorophyll concentrations off the Washington coast. Their research suggests that differences in CDOM between Washington and Oregon may be a partial explanation for perceived trends in satellite-derived chlorophyll. However, greater temporal and spatial coverage of OOI data sets is needed to more conclusively link physical forcing and biogeochemical responses.

Barth et al. (in press) use OOI Endurance Array data to describe a low-oxygen event off central Oregon. Changes in near-bottom oxygen off central Oregon vary through the summer season (Adams et al., 2013), but can also vary on the time scale of days as the wind-driven upwelling circulation advects the low dissolved oxygen pool back and forth across the shelf. Data from July 2017 illustrate this variability when several upwelling-favorable (southward) and downwelling-favorable (northward) wind events lasting from 2 to 10 days influenced near-bottom oxygen off Newport, Oregon (**Figure 6**).

During this time, near-bottom dissolved oxygen levels at the bottom of the OOI Oregon Inshore Surface mooring were often below the hypoxia threshold. When winds blow to the south, the near-bottom temperature decreases due to coastal upwelling, with a slight lag relative to the wind. During these upwelling events, near-bottom oxygen usually decreases, a good example of which is from 23 to 25 July. Conversely, during wind relaxation or downwelling the near-bottom temperature and dissolved oxygen increase rapidly. These changes are consistent with the upwelling circulation drawing near-bottom cold water low in dissolved oxygen toward the coast during upwelling and pushing warm water containing more oxygen down and away from the coast near the bottom during downwelling. The dissolved oxygen does not follow the winds or temperature as clearly as temperature follows the wind because there are the additional biological processes of photosynthesis and microbial decay that raise or lower dissolved oxygen levels, respectively. Since this report, OOI data continue to be used to characterize hypoxia in summer 2018. There is increasing interest in, and use of, OOI data by mission oriented agencies such as the Oregon Department of Fish and Wildlife.

From a larger northeast Pacific perspective, the Endurance Array is part of a more extensive observational capability in this region that includes the OOI Cabled Array, the OOI global site at Station Papa augmented by National Oceanic and Atmospheric Administration (NOAA) assets (see Section "Global Arrays"), the Ocean Networks Canada NEPTUNE and VENUS arrays, observations acquired by the Northwest Association of Networked Ocean Observing Systems (NANOOS) and other assets (see Barth et al., in press). This combination of ocean observatories allows regional climate and ocean phenomena to be tracked from formation to impact. An excellent example, predicted during the design phase of the OOI, was the formation of an anomalous "Warm Blob" in the Gulf of Alaska during late 2013 and early 2014 and its subsequent spread to the US west coast over recent years (Bond et al., 2015).

COASTAL PIONEER ARRAY

Science Drivers

The primary science driver for the Pioneer Array is understanding the processes of cross-frontal exchange between the continental shelf and slope, and their relation to synoptic, seasonal, and inter-annual forcing. The Pioneer Array is most closely aligned with themes (1), (2) and (4) of the OOI (ORION Executive Steering Committee, 2005): ocean-atmosphere exchange, climate variability, ocean circulation and ecosystems, and coastal ocean dynamics and ecosystems. The key science question articulated in the OOI Science Prospectus (ORION Executive Steering Committee, 2007) remains valid: How do shelf/slope exchange processes structure the physics, chemistry, and biology of continental shelves? This overarching question was refined at a 2011 community workshop to include four additional concepts: nutrient and carbon cycling; phytoplankton production, distribution, and diversity; extreme events, including winter storms and hurricanes; and controls on distribution and abundance of zooplankton and higher trophic levels.

Exchange processes transferring heat, salt, nutrients and organic matter between continental shelves and the deep sea are complex due to spatial and temporal complexity on a range of scales. Horizontal scales range from a few kilometers to 100 km, while vertical scales range from a few meters to the full water column (~100 m). It is difficult for a given observing platform type to effectively observe this range of scales. Some exchange processes occur over a few days and others may be sustained for months. Extreme events such as storms and the interaction of Gulf Stream eddies and filaments play important roles in exchange, but intermittent and only occasionally observed by expeditionary observing approaches.

The Pioneer Array is located over the continental shelf and slope in the Northwest Atlantic Ocean, centered about 80 nm south of Cape Cod (**Figure 7**). The characteristic dynamical feature in the region is the shelfbreak front. The front separates relatively cold, fresh water on the continental shelf from the warmer saltier water of the slope sea. The front is typically located near break in topography between shelf and slope – roughly the 150 m isobath. The Pioneer Array location was chosen to focus on frontal processes and to minimize the influence of other features such as canyons, river outflows, and the Gulf Stream. Prior process studies in the region provided information about the horizontal, vertical, and temporal scales in the region, allowing a deliberate approach to array design (Gawarkiewicz and Plueddemann, in press).

Infrastructure

In order to resolve multiple spatial scales, the Pioneer Array contains a combination of fixed and mobile platforms (**Figure 8**). The moored array is centered near the shelfbreak front and samples the shelf waters inshore and the slope sea offshore. Buoyancy-driven ocean gliders patrol the frontal region as well as the slope sea to the south. Propeller-driven Autonomous Underwater Vehicles (AUVs) provide "snapshots" of cross- and along-shelf structure in the vicinity of the front.

The Pioneer moored array includes seven sites between 95 and 450 m depth and utilizes two different mooring types. CSMs are distinguished by a surface buoy with a 3 m tower which in includes telemetry systems, power generation from solar panels and wind turbines, and sensors for meteorological and sea-surface observations. CSMs also have a Near Surface Instrument Frame (NSIF) at 7 m depth and an instrumented Multi-Function Node (MFN) on the sea floor that incorporates an anchor. The NSIF and MFN support an interdisciplinary sensor suite measuring a variety of essential ocean variables (see Section "Infrastructure"). The CSM mooring riser contains stretch hoses with coiled conductors that provide electrical connectivity for power and communication from the buoy to instruments on the NSIF and MFN. CPMs are distinguished by McLane wire-following profilers which travel up and down a section of jacketed wire rope and upward-looking Acoustic Doppler Profilers mounted below the lower profiler bump-stop. Instrumentation on the CPMs is the same as described for the Endurance Array (Section "Infrastructure"). CPMs have surface buoys with communication systems analogous to those on the CSMs, but do not carry instrumentation or power generation equipment. Specially designed systems associated with the MFN and the CPM anchors allow all Pioneer Array mooring anchors to be recovered and reused.

In winter, there are ten moorings occupying the seven Pioneer sites; all sites contain CPMs and three sites contain both CSM and CPM. In summer, CPMs at the central and inshore sites are replaced by profiling gliders (see description below). The mooring array spans along- and across-shelf distances of 9 and 47 km, respectively, and moorings are separated from each other by distances of 9.2 to 17.5 km. At the inshore (95 m) and offshore (450 m) ends of the array, there are mooring sites along the same isobath separated by 9 km, intended to provide the ability to estimate cross-shore gradients and property fluxes.

To provide multiscale observations of the frontal region, and the slope sea, the mooring array is supplemented by two types of autonomous vehicles. Coastal Gliders are custom configurations of the Teledyne Webb Research Slocum G2, and are designed for shallow-water operations (either 200 m or 1000 m buoyancy engines). Six track-line following gliders are piloted along five pre-defined routes within the glider operating area of 185 km × 130 km. Two profiling gliders, which "hold station" to provide a virtual mooring, are operated at inshore and central Pioneer Array sites in summer. This provides observations of near-surface stratification that would be missed by CPMs. The Pioneer gliders have a nominal three-month deployment and refurbishment cycle and carry the same sensors as the Endurance gliders. The two Pioneer AUVs are Kongsberg-Hydroid REMUS-600 vehicles with a payload customized to meet OOI science requirements. Variables measured match those of the gliders, while adding velocity profiles and nitrate. Although the original

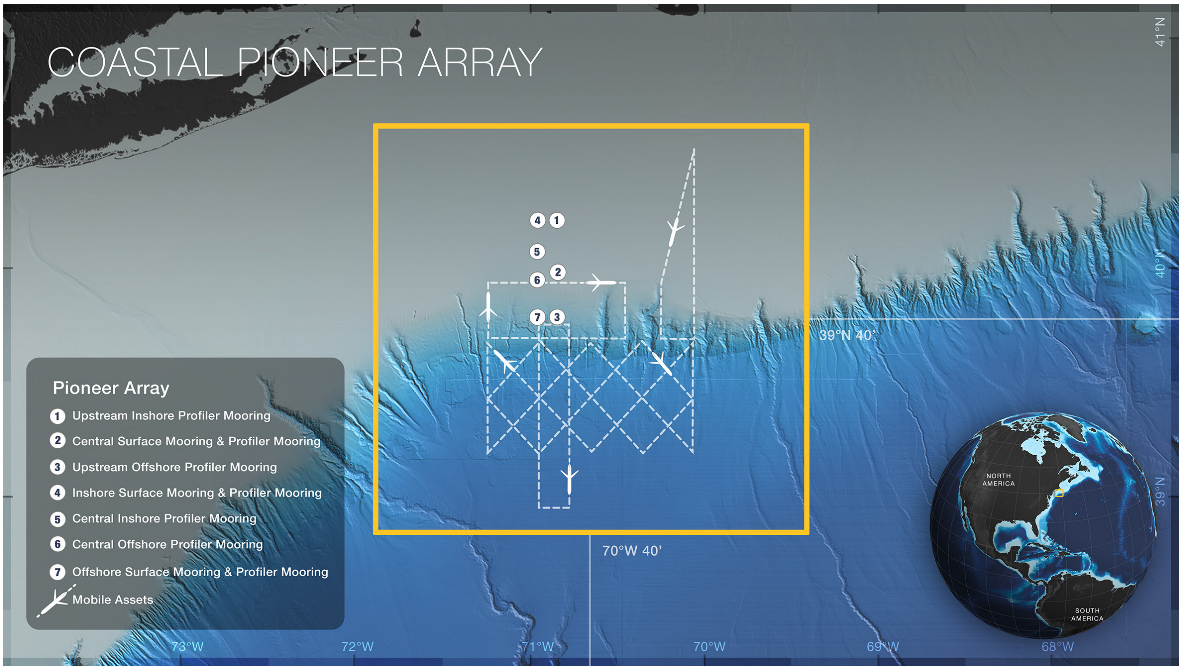

FIGURE 7 | The Pioneer Array mooring locations (numbered dots) and glider track lines (dashed) are shown relative to the northeast US continental shelf and slope. The AUVs operate in the vicinity of the moored array. The shelfbreak front is a persistent feature found where the relatively flat shelf transitions to the slope (indicated by the bathymetry color change). Figure credit: Center for Environmental Visualization, UW School of Oceanography.

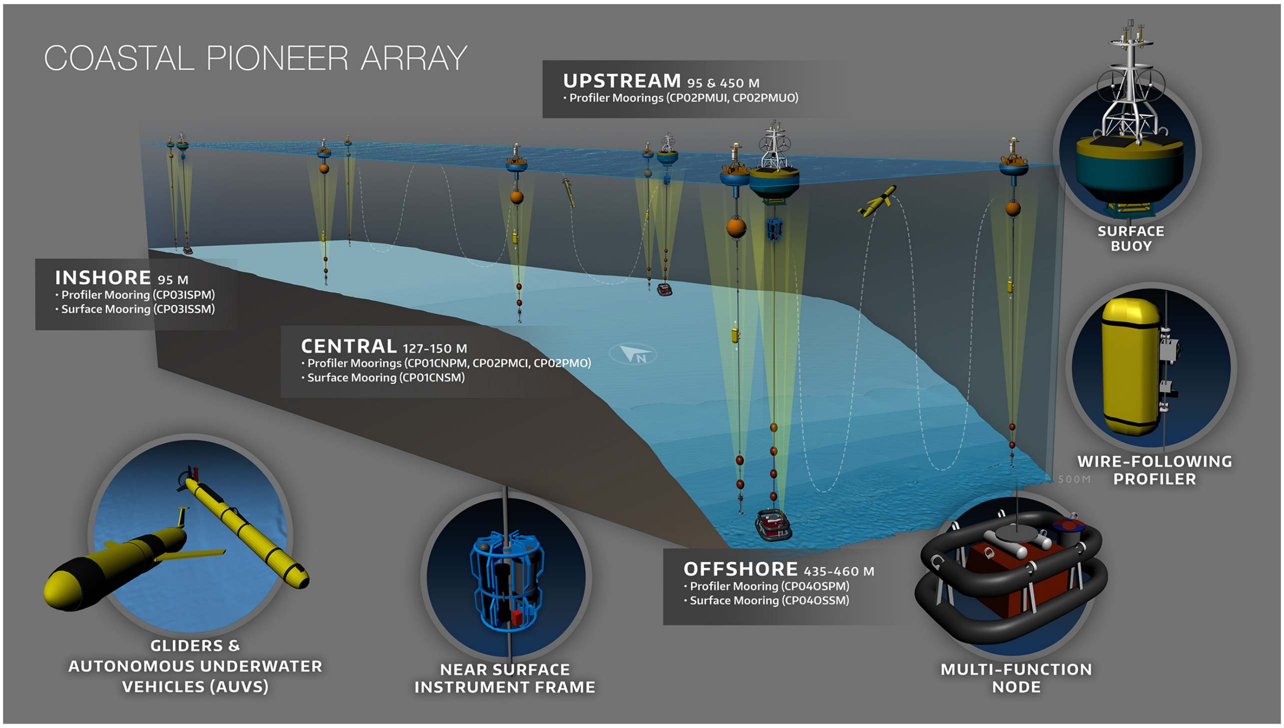

FIGURE 8 | Schematic of the Pioneer Array showing the moored array spanning the continental shelf and slope and representations of glider and AUV track lines. Breakouts highlight major array elements. Figure credit: Center for Environmental Visualization, UW School of Oceanography.

vision was for the AUVs to be operated from and recharged by seafloor docking stations, a decision was made in 2016 to operate the AUVs in campaign mode from ships. The nominal AUV missions are 14 km × 47 km rectangles centered on the mooring array, one oriented along-shelf and one oriented cross-shelf.

Science Highlights

A variety of scientific results utilizing Pioneer Array data are published or in progress, and views of the New England shelfbreak region are changing. Gawarkiewicz et al. (2018) provide a recent review, noting that that slope waters have been warmer and saltier, while anomalous onshore intrusions of warm, salty water associated with warm core rings appear to be more frequent and penetrate further inshore. Selected examples of Pioneer-related science results are provided below.

Pre-commissioned data from OOI were used in a study of an unusual northward excursion of the Gulf Stream path in October 2011, combined with a large meander that brought that warm, salty water to the shelfbreak south of New England (Gawarkiewicz and Plueddemann, in press). The presence of warm water in the region was noted by the New England commercial fishing community. Near-bottom temperature measurements from lobster traps on the outer continental shelf showed distinct warming events (temperature increases exceeding 6°C). OOI Wire Following Profiler measurements, from a site at about 500 m depth over the continental slope, confirmed high salinities associated with the high temperatures, indicating that the warm water on the continental shelf originated in the Gulf Stream.

A possible explanation for the increase in Gulf Stream interactions a change in location of the Gulf Stream destabilization point – where meandering (which eventually leads to instabilities and eddies) begins. Andres (2016) used satellite altimetry data to show that the destabilization point has shifted to the west, and that this has changed increased the frequency of eddies in the MAB.

Pre-commissioned data from Pioneer gliders were used along with satellite SST imagery to document an intrusion of Gulf Stream warm-core ring water onto the Mid-Atlantic Bight continental shelf (**Figure 9**; Zhang and Gawarkiewicz, 2015). The authors argue that this is a previously unknown exchange process, with the intrusion extending hundreds of kilometers to the southwest along the shelfbreak. Idealized numerical simulations, indicate that the intrusion results from topographically induced vorticity variation of the ring water, rather than from entrainment in the shelfbreak frontal jet. Such intrusions have important biogeochemical implications, such as facilitating migration of marine species across the shelfbreak barrier and transporting low-nutrient surface Gulf Stream ring water to the otherwise productive shelfbreak region.

GLOBAL ARRAYS

Science Drivers

Leading science themes for OOI motivated the initial design of the global arrays: ocean-atmosphere exchange; climate variability, ocean circulation and ecosystems; turbulent mixing and biophysical interactions; and modeling and data assimilation. The Final Network Design added foci on ocean ecosystem health, climate change, carbon cycling, and ocean acidification. Aware of the sparseness of ocean sampling at high latitude regions, community consensus was that the most pressing need was for sustained, multidisciplinary observations at key high latitude sites. Further, the need was for time series capturing the range of variability from the high frequencies and episodic events to decadal and multidecadal modes. These high latitude regions, though critical to understanding the ocean's role in the earth system, were not yet being observed in a comprehensive, sustained way due to the technical challenge.

Considerable discussion and community input led to the identification of the sites for the OOI global nodes. In addition to having high regional scientific merit, the desire was to sample contrasting or different biological or biogeochemical regimes. **Figure 10** shows maps that were used in planning. Very energetic air-sea interaction accompanies the very strong winds south of about 50°S, in the North Atlantic southeast of Greenland, and in the Gulf of Alaska. High ocean heat loss there contributes to the production of the deep and intermediate waters. With little *in situ* data from these regions, model-based and other characterizations of the air-sea fluxes of heat, fresh water, momentum, CO_2, and other properties have error and uncertainty, so *in situ* observations of the surface meteorology and air-sea fluxes, including direct covariance flux observations of the turbulent fluxes, would have great value in building improved understanding of air-sea interaction at high latitudes, of water mass formation, and of the phytoplankton blooms found there. Maps of air-sea CO_2 flux show flux into the ocean in the high latitude North Atlantic, North Pacific, and South Atlantic; but the southeast South Pacific does not show in this map flux into the ocean. Yet, maps of column inventory CO_2 not only show elevated anthropogenic CO_2 inventory close to the source and to where deep-water forms, but also show elevated column inventory levels in the South Atlantic, South Indian Ocean, and southeast South Pacific, suggesting that thermohaline circulation as well as air-sea fluxes contribute to the column inventory and add to the motivation to investigate the air-sea exchanges and sequestration of carbon at high latitudes. From a perspective of biological productivity, SeaWiFS imagery highlights a strong chlorophyll signal in the high latitude North Atlantic, a moderate signal in the high latitude North Pacific, a localized region of productivity off the coast of southern Argentina in the South Atlantic, and little productivity in the southeast South Pacific. As the design was advanced for the global array, there was speculation that while productivity had no limiting factors in the North Atlantic, the southeast South Pacific and Gulf of Alaska might be nutrient rich but iron limited and the southwest South Pacific might also nutrient rich but iron limited except when it received dust and aerosols from the South American continent. *In situ* sampling of biology and nutrients at high latitudes was needed to investigate further.

Thus, the plan matured to occupy two sites in the northern hemisphere and two in the southern hemisphere; all would

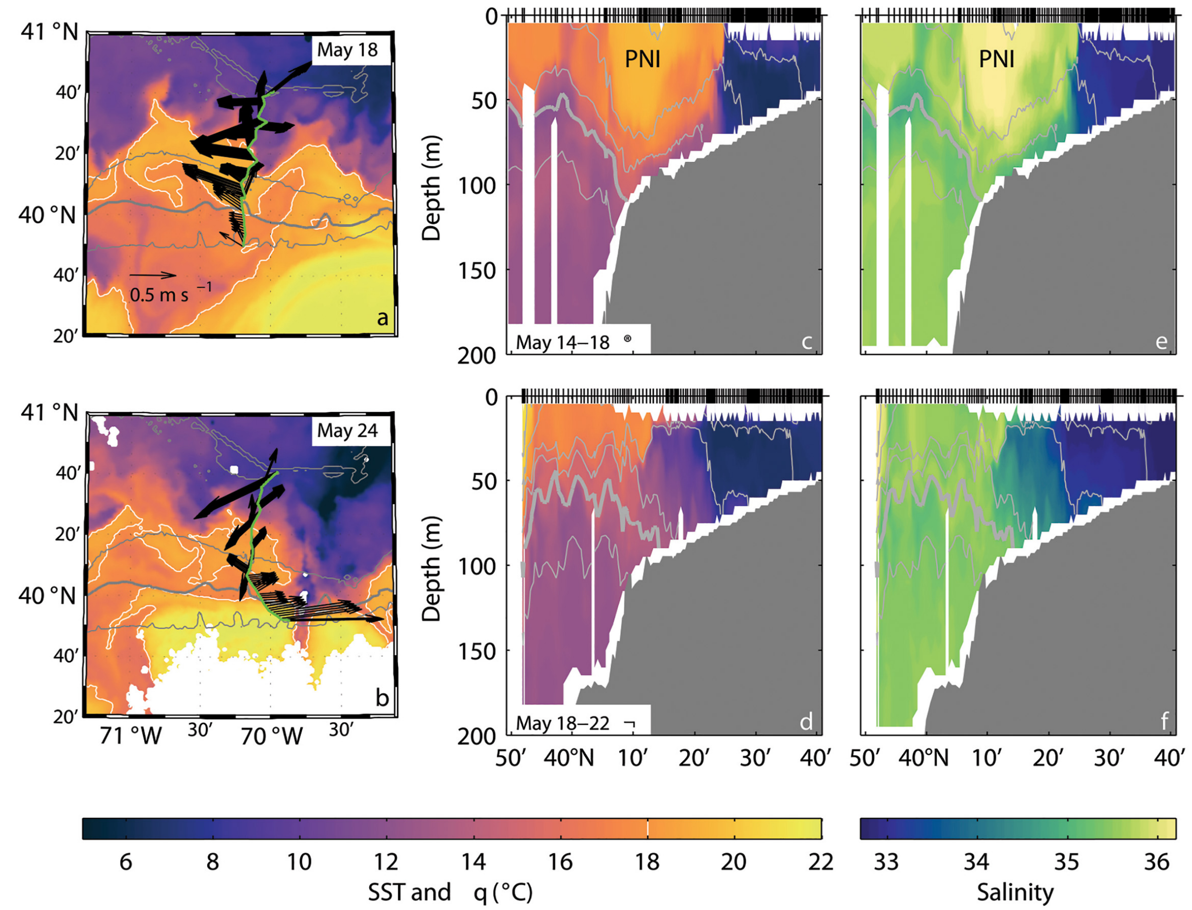

FIGURE 9 | Rapid evolution of temperature and salinity at the Pioneer Array observed by gliders. **(a)** Sea surface temperature (SST) on 18 May 2014 with the 18°C isotherm highlighted (white). **(b)** SST on 24 May 2014. **(c)** potential temperature, and **(e)** salinity from a glider during 14–18 May; PNI denotes an intrusion. **(d,f)** Show the same properties as **(c,e)** a few days later. In **(a,b)**, the trajectory of the glider (green) and vertically averaged current vectors are shown. Gray contours are the 50, 100, 200 (bold), and 1,000 m isobaths. In **(c,d)**, isopycnals are shown in gray, with a contour interval of 0.25 kg m^{-3}. Tick marks on the upper axes denote locations of glider profiles. Arrows indicate the direction of glider motion during the indicated dates. (Adapted from Gawarkiewicz et al., 2018). Reproduced with permission from the Oceanography Society.

be strongly forced, but there would be contrast in the carbon and biological regimes. In addition, sites with different ocean dynamics were sought.

The sites chosen included the Irminger Sea (60°N, 39°W), the Southern Ocean (55°S, 90°W), the Argentine Basin (42°S, 42°W), and the Gulf of Alaska (50°N, 145°W). The Gulf of Alaska had an existing NOAA surface mooring, and OOI planned to add to that site to match the other global sites. Observing requirements included sampling: surface forcing (surface meteorology, air-sea fluxes), the full water column (sea surface to sea floor), and the mesoscale and smaller scale horizontal structure and variability.

The Irminger Sea site was identified early in the planning as of the highest priority. Some of the strongest regional atmospheric forcing occurs there. Shipboard sampling had shown water column freshening in the Denmark Straits and Faroe-Shetland Channel (Dickson et al., 2002) region of the high latitude North Atlantic for decades, and international attention has focused on potential changes that could result in the large-scale thermohaline circulation if freshening arrested deep convection. Key questions about this site include: What are the processes that form the deeper water? What is the role of regional air-sea interaction? What are the roles of the ocean mesoscale and 3-D processes in water mass transformation? Is the ongoing freshening of the water in the region having an impact on the water mass transformation and thermohaline circulation? These questions can be addressed by an OOI global node, which observes the surface forcing, samples the mesoscale, and has a planned duration of deployment of 20 to 25 years. Further, the sampling by the global node would sample year-round and capture episodic and strong forcing events most likely missed in the historical record of shipboard sampling. An international effort, the Overturning in the Subpolar North Atlantic Program (OSNAP, Lozier et al., 2017), planned to deploy a line of subsurface moorings spanning the North Atlantic, from the United Kingdom to Greenland and then from Greenland to Canada to measure transports to and from the northern North

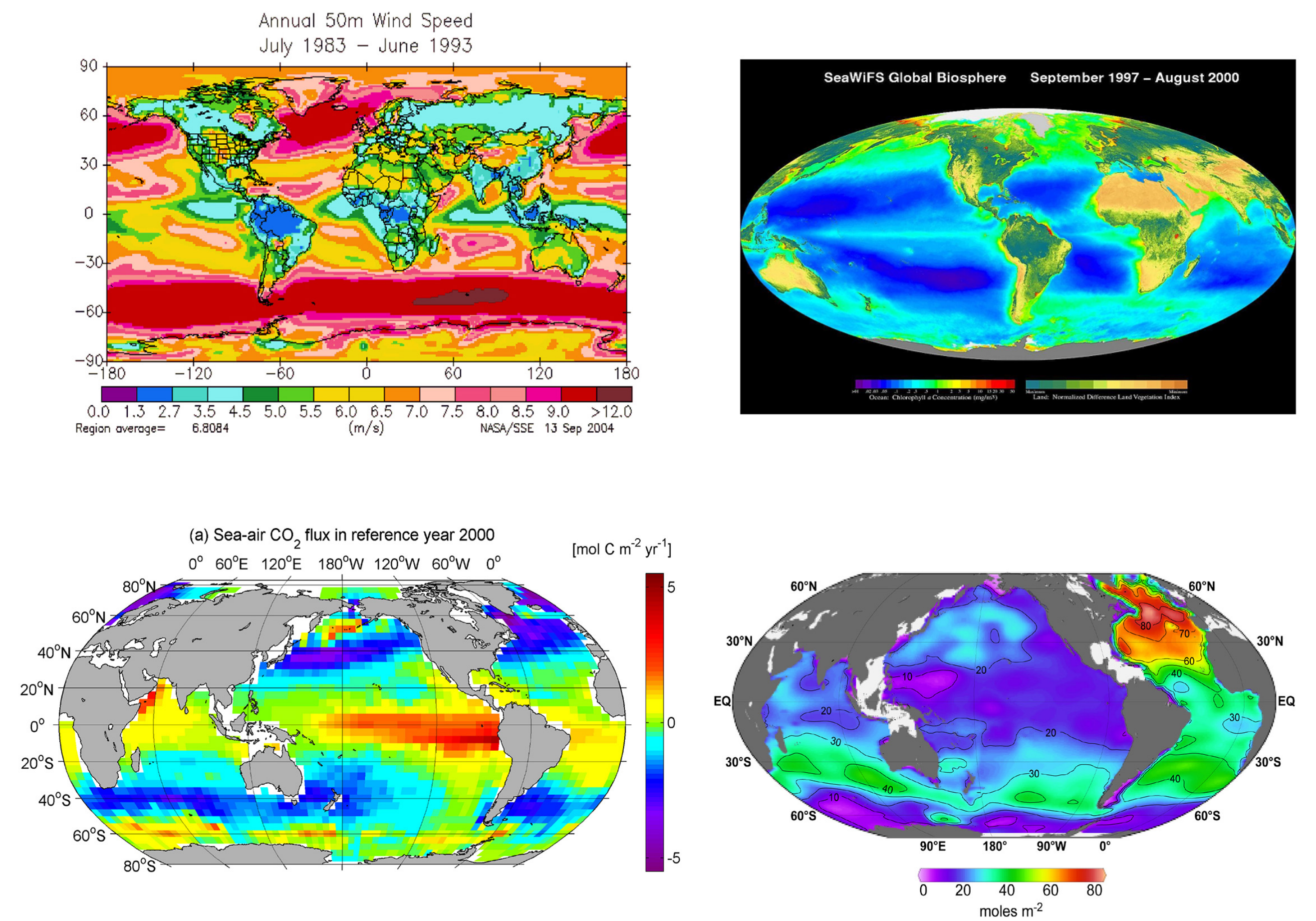

FIGURE 10 | Upper left, 10-year mean wind speeds at 50 m height, from https://upload.wikimedia.org/wikipedia/commons/4/46/Global_Annual_50m_Average_Wind_Speed.png; upper right, long term mean chlorophyll from SeaWiFS, from https://earthobservatory.nasa.gov; lower left, atmosphere-ocean exchange of CO_2 in 2000, from https://www.pmel.noaa.gov/co2/files/fluxmap.jpg; lower right, anthropogenic CO_2 column inventory from Sabine et al. (2004), from https://www.pmel.noaa.gov/co2/file/column+inventory+of+anthropogenic+CO2.

Atlantic. Siting of OOI Irminger Sea node was coordinated with OSNAP, with the two flanking moorings placed in the OSNAP line of moorings. OOI selection of the Irminger Sea also reflected community interest in the global ocean carbon cycle, consideration of biological productivity, and desire to support investigation of links between ecosystems and climate. The Irminger Sea region is an area with a high level of anthropogenic CO_2 and a large flux of CO_2 into the ocean (Takahashi et al., 2002; Sabine et al., 2004). It also has as strong spring bloom. The covariability of species such as Calanus with climate variability in the region has been studied (Gislason et al., 2015) as has the poleward migration of marine species in response to climate variability (Sundby et al., 2016). Thus, the Irminger Sea site's data would support study of a region with high wind and large surface waves, strong atmosphere-ocean exchanges of energy and gases, deep water formation and CO_2 sequestration, high biological productivity and an important fishery, and a climate sensitive ecosystem. Further, it represented a convergence and collaboration of US ocean science studies and observing with European ocean science and observing efforts.

Another high priority site identified in planning the global OOI nodes was the high latitude South Pacific. The region near 55°S, 90°W, to the west of the southern tip of Chile, is important from the perspective of the large-scale thermohaline circulation and had been a focus for study on intermediate water formation (e.g., Sloyan et al., 2010). Like the Irminger Sea it is strongly forced and a region of CO_2 sequestration with a large fetch and powerful storms regularly moving west to east. This site would provide new insight into the challenges that weather, climate, and ocean models face in regions where very little data exist for initialization and for verification. It would also provide data important to improved understanding of the Southern Ocean and of links between the Southern Ocean and the Antarctic (National Research Council [NRC], 2015), including the strengthening westerly winds and their role in increased upwelling of warmer waters around the Antarctic continent's ice shelves. Like the Irminger Sea site, there was interest in regional collaboration, and Chilean oceanographers and meteorologists looked forward to data from this site, which is located in a region where weather systems that move toward Chile originate. From a biological perspective, the Southern Ocean site provided a sought-after contrast with the Irminger Sea, as although it was nutrient rich it had low biological productivity due to iron limitation (Morrissey and Bowler, 2012). Further, from a climate perspective, whereas climate models pointed to a warmer and fresher water column in the Irminger Sea, climate models suggested a cooling of surface waters off southern Chile.

As planning proceeded, the NSF placed increasing emphasis on investigating the carbon cycle. This elevated the priority placed on occupying a southern hemisphere location of high biological productivity and led to the selection of the site at 42°S, 42°W in the Argentine Basin, where high biological productivity is evident in SeaWiFS imagery. Productivity is believed to be limited by iron, but there is also the possibility that micronutrients reach that region when transported from the continent in dust (Li et al., 2008). There is also CO_2 sequestration, and strong atmospheric forcing. Unique to this site in the global OOI array are very strong currents and elevated eddy kinetic energy. Strong currents reach the seafloor and suspended particulate matter (Richardson et al., 1993) and mud waves on the sea floor (Flood and Shor, 1988) have been studied there in the past. Eddy kinetic energy levels are similar there to those in the Gulf Stream (Stammer, 1997), and the site will be an excellent location for investigation of mesoscale variability and its role in ocean processes. The confluence of currents there leads to interest in the interaction of different water masses and exchange between gyres of mass, heat and salt there (e.g., Jullion et al., 2010). In planning this site, interest arose from physical oceanographers and fisheries scientists in Argentina and from the UK GEOTRACES program, which planned a shipboard sampling line to investigate cycles of trace elements and isotopes that would pass near the site and through the Argentine Basin.

The fourth global OOI site was in the Gulf of Alaska at the historical location of Ocean Weather Station PAPA (50°N, 145°W). Observing at this site has had a long history. Over the years, PAPA data was used in the development of ocean models. Canadian oceanographers have maintained shipboard sampling in the years following the removal of the weather ship. PAPA adds a contrasting regime OOI global node array. There is CO_2 sequestration, but the site has the lowest level of anthropogenic CO_2 of the four global nodes. Biologically productivity is thought to be limited by iron, but the region has an important and productive fishery. There is long-period variability related to the Pacific Decadal Oscillation, which may be reflected in the biology as well as in physical variability. PAPA has low eddy variability compared to the other sites. PAPA could form the basis for ongoing collaboration with Canadian oceanographers and with NOAA Pacific Marine Environmental Laboratory (PMEL).

Global Array Design

The scientific drivers set the capabilities required at a global node to address the science: surface meteorology and air-sea fluxes, including of CO_2; structure and variability of temperature, salinity, and velocity from the sea surface to the sea floor; biological and chemical sampling, including of pH, chlorophyll, biomass, and nutrients; and provision of as much data as possible to users in near real time. While sampling in the upper ocean, including the euphotic zone and the surface mixed layer and seasonal thermocline, the ability to obtain observations with good vertical resolution up to and through the sea surface was sought. In addition, the goal was to push beyond sampling in time and just the vertical dimension, and to provide the capabilities to sample the horizontal variability at the mesoscale and smaller scales. The design of an OOI global scale node developed for high latitude deployment is shown in **Figure 11**.

Four moorings are at each site, pairing a surface mooring and a taut subsurface mooring with a profiler together at one corner of the triangular moored array and placing two taut subsurface moorings called Flanking Moorings at the other corners of the triangle. To complement the moorings, two ocean gliders are deployed to sample in scales within and around the moored array and two more gliders collect vertical profiles up through the sea surface. Thus one corner of the triangle provides the sampling from the sea surface to the sea floor. The surface mooring has a well-instrumented surface buoy and carries ocean sensors in the upper 200 m of the water column. To sample the full water column, the adjacent taut subsurface mooring is deployed next to the surface mooring with profiling instruments that move up and down the wire rope, covering the depths not sampled by the surface mooring. The full water column and surface sampling at that corner is complemented by taut subsurface moorings at the other two corners. These moorings, the flanking moorings, have surface flotation close to 30 m and discrete instruments at fixed depths. The sides of the mooring triangle are roughly 10 times the water depth, with the intent of sampling the variability associated with the characteristic eddy scales. Additional sampling of spatial variability within and around the moored array was to be done with ocean gilders. Community input emphasized the importance of near-surface profiles that penetrated the sea surface, and two ocean gliders were included in the global node design to obtain profiles through the sea surface.

Further design features were driven by environmental conditions. The height of the tower of the surface buoy was set at 5 m in recognition of the anticipated sea states and freezing spray. The surface buoy had comprehensive and redundant telemetry systems including Fleet Broadband. To support these systems and provide power up to about 200 W, rechargeable lead-acid batteries together with wind turbines and solar panels were mounted. Two redundant bulk meteorological systems were deployed together with a direct covariance flux system at Irminger and Southern Ocean. Access to the data from the subsurface moorings and the ability to interact with them was planned via ocean gliders. The subsurface moorings had controllers that aggregated data from instruments. Gliders with acoustic modems downloaded these observations and when back at the surface telemetered these data and could carry commands from shore back to the subsurface moorings The two vertically profiling gliders carried between them a 3-wavelength fluorometer, a CTD, dissolved oxygen sensor, nitrate sensor, and a photosynthetically available radiation sensor. The gliders tasked to sample within the volume of the moored array dove to 1,000 m and carried a 2-wavelength fluorometer, CTD, and dissolved oxygen sensor.

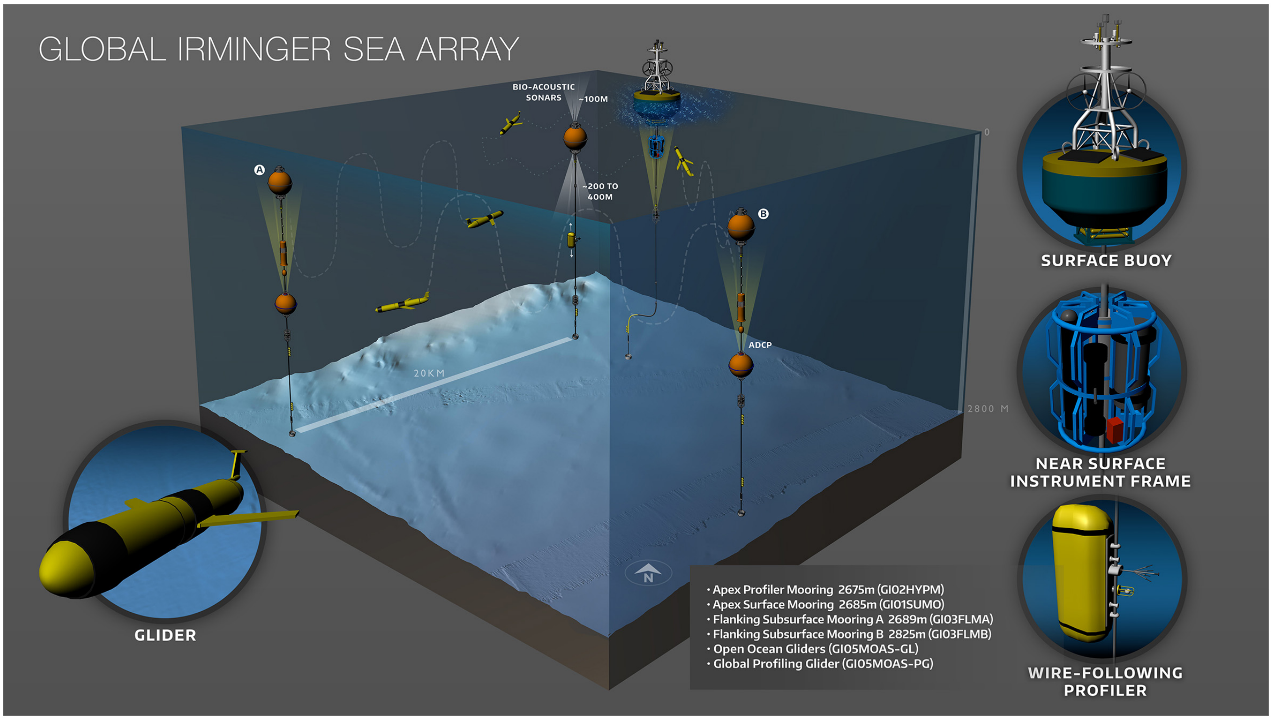

FIGURE 11 | A schematic of the Global Irminger Sea Array, with four moorings and several ocean gliders. Figure credit: Center for Environmental Visualization, UW School of Oceanography.

Science Highlights

Very strong air-sea fluxes of heat and momentum are anticipated at the Southern Ocean. Ogle et al. (2018) found episodic heat loss events with daily mean ocean het losses of up to –294 W m^{-2} in association with cold, dry air from the southwest. These extreme heat losses lead to convective deepening of the mixed layer and formation of Subantarctic Mode Water. **Figure 12** (from Ogle et al., 2018) illustrates the strong surface forcing and resultant deep mixed layer formation.

Early results from the OOI moorings at the Irminger site and the nearby German Central Irminger Sea (CIS) and Dutch Long-Term Ocean Circulation Observations (LOCO) moorings have captured winter time convection events in the winters of 2014–2015 and 2015–2016 and stimulated great interest the observed spatial variability in the winter deep convection (de Jong et al., 2018). **Figure 13**, taken from that paper, is an amazing distillation of the surface forcing and ocean observations across the six moorings. Strong eddy variability was evident and the role of these eddies in modulating surface layer response to the atmosphere is of great interest. In addition, the biological and biogeochemical data from the array are being used to better understand the biological pump that transports carbon into the deep ocean and the contributions to the biological pump from the spring bloom of plankton as well as the deep winter mixed layer formation and accompanying sinking of particles (Palevsky and Nicholson, 2018).

THE FUTURE

Submarine cabled observatories are an emerging technological trend as shown by the installation of observatories in Japan, Taiwan, Norway, China, and Canada, as well as numerous smaller ones in the Mediterranean (Delaney and Kelley, 2015). The provision of high bandwidth and power to submarine cables that span tectonic plates, full ocean depths, and coastal marine environments provides powerful infrastructure/facilities to optimize next-generation science in the ocean basins by fully capitalizing on a suite of emergent technologies. These cutting edge capabilities include, but are not limited to, nanotechnology, biotechnology, information technology, *in situ* genomic analysis, mass spectrometry, computational modeling, imaging technologies, and robotics. More powerful than any single technology will be their progressive integration into highly sophisticated submarine systems designed to conduct challenging remote operations in novel ways coupled with Cloud Computing and Ocean Informatics.

Science questions pertaining to coastal ocean dynamics and ecosystems change drove much of the design of the Endurance Array. Science drivers such as hypoxia, ocean acidification, swings between zooplankton species, and harmful algal blooms remain a focus of the array. However, in the 10 years since the array design, additional significant, and in some cases unanticipated, rapid ecosystem changes have been observed. The recent 2013–2015 warm "blob" event drove significant ecosystem changes in the Endurance Array region (Cavole et al., 2016)

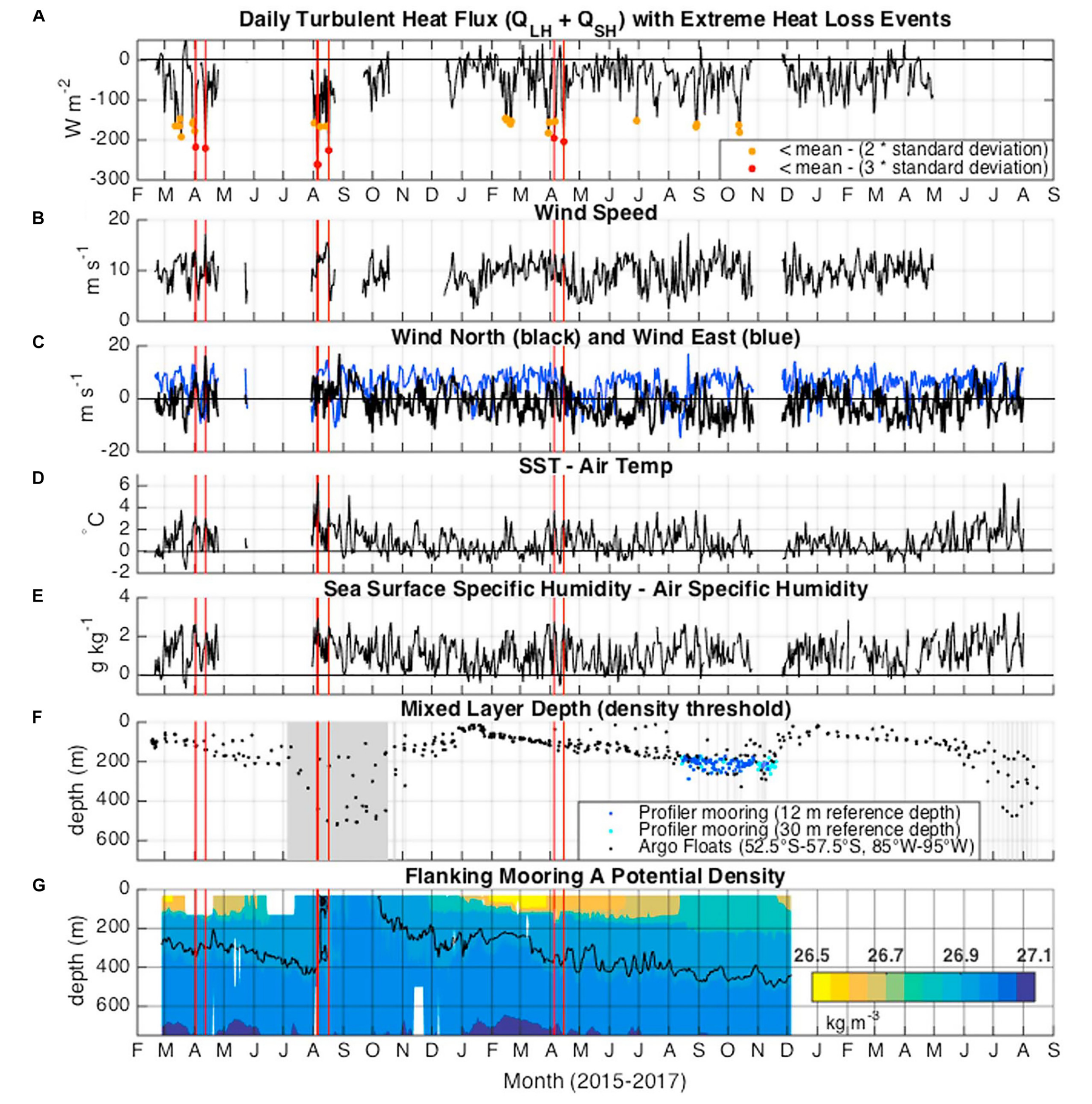

FIGURE 12 | Figure 3 from Ogle et al. (2018) shows in panel **(A)** the sum of the daily latent and sensible heat losses, with extreme events marked in red, in panel **(B)** the relative wind speed, in panel **(C)** the north (black) and east (blue) wind components, in panel **(D)** the air-temperature gradient, SST minus air temperature, in panel **(E)** the air-sea humidity gradient, surface saturated specific humidity minus buoy specific humidity, in panel **(F)** mixed layer depths from Argo floats and the profiler mooring, and in panel **(G)** a contour plot of potential density with the black line the boundary of Subantarctic Mode Water. Reproduced with permission from the American Geophysical Union and from John Wiley and Sons.

including shifts in species composition. Events like sea star wasting disease (Menge et al., 2016) and the recent abundance of pyrosomes off Oregon and Washington (Sutherland et al., 2018) may be a preview of long term changes in the region. The Endurance Array glider grid occupies the northern end of a west-coast underwater glider array that spans from the Strait of Juan de Fuca in the north to San Diego, California, in the south, and includes about ten, long cross-margin lines. This glider array will be key to tracking the north-south progression of climate events into the Pacific Northwest from both the north (warm blob) and the south (El Niño/La Niña). Like other elements of OOI, the Endurance Array has the expansion

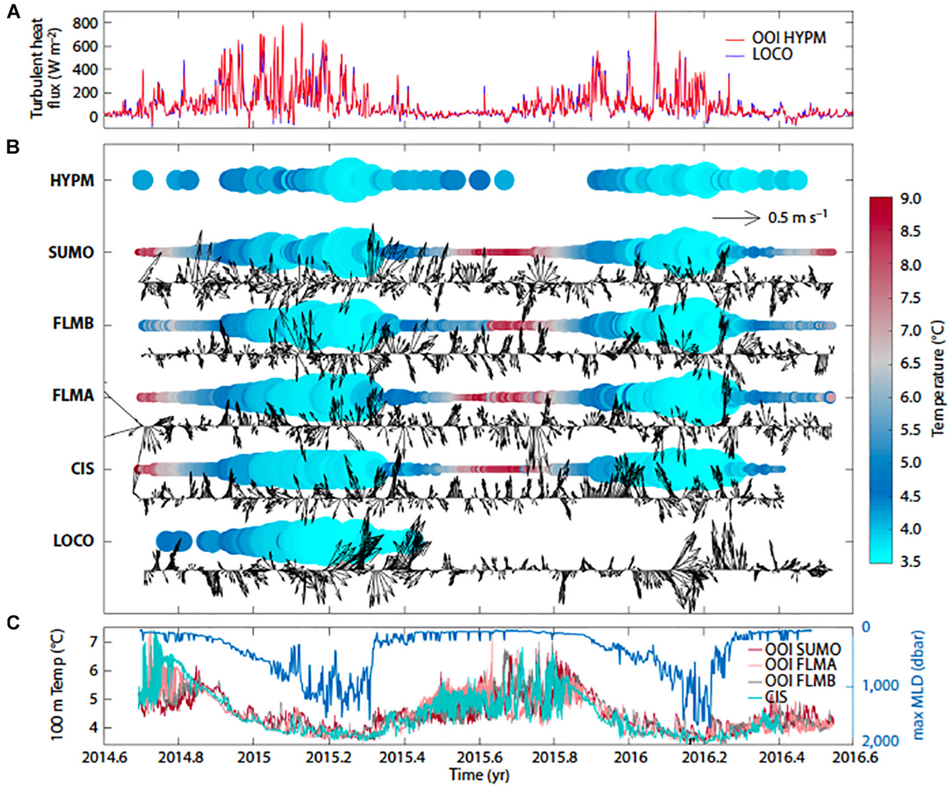

FIGURE 13 | From de Jong et al. (2018). **A** shows the turbulent heat flux at the most northerly mooring OOI HYPM) and most southerly mooring (LOCO). **B** summarizes mixed layer depth (size of the shaded circles) and temperature (color) and velocities (arrows). **C** shows daily maximum mixed layer depth (blue) and 100 m depth temperatures from four of the moorings. Reproduced with permission from the Oceanography Society.

capability to accommodate sensors added by individual principal investigators. The Endurance Array and Cabled Array can host additional hydrophones to help track tagged fish species of interest in the Pacific Northwest, e.g., green sturgeon that occupy similar isobaths ranges as anticipated marine renewable energy devices. Emerging technologies such as genomic sensors (e.g., harmful algal blooms (HABs), eDNA, toxins), and imaging sensors (e.g., plankton) together with the long term core physical, chemical and biological measurements on the Endurance Array would be a powerful combination and provide unique insights into regional ecosystem changes.

Recent research on shelf/slope processes in the Middle Atlantic Bight indicates long-term warming of the continental shelf (Forsyth et al., 2015) with potential impacts on ecosystems (Pershing et al., 2015; Hare et al., 2016), as well as anomalously warm years (Chen et al., 2014) that have impacts on commercial fisheries (Mills et al., 2013; Gawarkiewicz et al., 2018). New processes (Zhang and Gawarkiewicz, 2015) and unusual phenomena (Gawarkiewicz and Plueddemann, in press) impacting shelf/slope exchange have been exposed as offshore forcing, perhaps due to a change in the destabilization point of the Gulf Stream (Andres, 2016), appears to be increasingly important. The mean frontal conditions appear to be impacted by these changes (Gawarkiewicz et al., 2018). The impact of anomalous warming and extreme shelf/slope exchange events on commercial fisheries has already been realized, and it is likely that such disruptions will continue. Within this backdrop of environmental change and societal impacts, the sustained, multi-scale, multi-platform observations from the Pioneer Array are of increasing importance. The Pioneer Array supports a Northeast US Shelf (NES) Long-Term Ecological Research (LTER) program funded by the NSF[2]. The Pioneer Array is anticipated to have impacts beyond the Middle Atlantic Bight. For example, there is interest in developing shelf and shelfbreak observatories in the East China Sea, the South China Sea, the Bay of Bengal and the Norwegian coast. The approach to design and implementation of the Pioneer Array serves as guidance for these efforts (Gawarkiewicz and Plueddemann, in press). Furthermore, an open competition for relocation of the Pioneer Array is anticipated after 5 years of operation, which will stimulate new scientific applications in new geographic regions that can benefit from the Array infrastructure.

The two southern hemisphere sites fill large areas of data sparse ocean. They have been brought in under the umbrella of the Southern Ocean Observing Serving (SOOS), an international group working to develop the Southern Ocean component of the Global Ocean Observing System (GOOS). The surface moorings from these sites and their data are drawing high

[2]https://nes-lter.whoi.edu

interest and use. Some investigators working to make global ocean fields of air-sea fluxes (the transfers of heat, freshwater and momentum) blends satellite observations together with data from the surface analyses from weather prediction models. They make an optimal combination by weighting the satellite and model data to correct for errors and biases. These investigators have found that quality time series from a surface buoy of air temperature and humidity, wind speed and direction, incoming solar and longwave radiation, rain, barometric pressure, and SST are needed to develop these adjustments and tunings and that the optimization varies region to region. The Southern Ocean and Argentine Basin are in cold, dry areas that require a region-specific tuning, and these investigators have used the surface mooring data from these sites. Continuation of the Southern Ocean array is desired to examine the interannual variability in the surface forcing, mixed layer deepening, and mode water formation.

The Southern Ocean site has drawn interest from investigators looking at change and variability in Antarctic. During the international Year of Polar Prediction-Southern Hemisphere (YOPP-SH), the predictability of Southern Ocean and Antarctic weather systems has been one focus. To test whether or not the Southern Ocean data would have impact on regional weather prediction Southern Ocean surface meteorology, data was passed on to the Global Telecommunication System (GTS) via the National Data Buoy Center (NDBC) allowing the European Centre for Medium Range Weather Forecasting (ECMWF) to conclude that the Southern Ocean surface mooring data improved the forecast of synoptic weather systems.

A workshop on Irminger Sea Regional Science was held in late 2017 at the National Oceanography Centre in Southampton, United Kingdom. At the highest level, there was high interest in the Irminger Node from several perspectives. First, the array was located where we believe there are very large ocean heat losses and where this cooling makes surface water dense, causing sinking or convection that converts surface water to the deeper water that flows southward as part of the large-scale global circulation. Improved understanding and prediction of the formation of deeper water at the surface in this region is the goal of many researchers. Second, there is a strong desire to get accurate observations of the air-sea fluxes in the Irminger Sea and thus improve understanding of how the atmosphere drives the formation of deep water there. So even though the Irminger Sea surface mooring has had challenges with icing; the four seasons of partial records are being analyzed and looked at as the means to identify errors and biases in model-based estimates of the air-sea fluxes. Josey et al. (2018) found that the winter of 2014–2015 had strong wind events associated with Greenland tip jets where hourly mean heat loss exceeded 800 W m^{-2}. Looking at following years, year to year variability in net heat loss was large and linked to the frequency of the Greenland tip jets. The workshop recommended: sustain OOI Irminger, including additional sampling on flanking moorings to match OSNAP; make every effort to improve data return on OOI Irminger surface buoy, with attention to the surface meteorology and air-sea fluxes, as these are key to improving understanding of the surface forcing for the region; deploy routinely gliders as their non-physical data provide unique, valued information; sustain the OOI Irminger profiler, as the Dutch LOCO and German CIS moorings will be discontinued and the OOI Irminger profiler used to return the profile data needed to observe deep convection and other processes.

AUTHOR CONTRIBUTIONS

JT coordinated and was responsible for section “Introduction.” DK, ED, AP, and RW were responsible for sections “Regional Cabled Array,” “Coastal Endurance Array,” “Coastal Pioneer Array,” and “ Global Arrays,” respectively. OK and JB contributed to sections “Regional Cabled Array” and “Coastal Endurance Array”. All authors contributed to section “The Future”.

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MINI REVIEW
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Putting It All Together: Adding Value to the Global Ocean and Climate Observing Systems With Complete Self-Consistent Ocean State and Parameter Estimates

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In 1999, the consortium on Estimating the Circulation and Climate of the Ocean (ECCO) set out to synthesize the hydrographic data collected by the World Ocean Circulation Experiment (WOCE) and the satellite sea surface height measurements into a complete and coherent description of the ocean, afforded by an ocean general circulation model. Twenty years later, the versatility of ECCO's estimation framework enables the production of global and regional ocean and sea-ice state estimates, that incorporate not only the initial suite of data and its successors, but nearly all data streams available today. New observations include measurements from Argo floats, marine mammal-based hydrography, satellite retrievals of ocean bottom pressure and sea surface salinity, as well as ice-tethered profiled data in polar regions. The framework also produces improved estimates of uncertain inputs, including initial conditions, surface atmospheric state variables, and mixing parameters. The freely available state estimates and related efforts are property-conserving, allowing closed budget calculations that are a requisite to detect, quantify, and understand the evolution of climate-relevant signals, as mandated by the Coupled Model Intercomparison Project Phase 6 (CMIP6) protocol. The solutions can be reproduced by users through provision of the underlying modeling and assimilation machinery. Regional efforts have spun off that offer increased spatial resolution to better resolve relevant processes. Emerging foci of ECCO are on a global sea level changes, in particular contributions from polar ice sheets, and the increased use of biogeochemical and ecosystem data to constrain global cycles of carbon, nitrogen and oxygen. Challenges in the coming decade include provision of uncertainties, informing observing system design, globally increased resolution, and moving toward a coupled Earth system estimation with consistent momentum, heat and freshwater fluxes between the ocean, atmosphere, cryosphere and land.

Keywords: ECCO, global ocean inverse modeling, optimal state and parameter estimation, adjoint method, ocean observations, coupled Earth system data assimilation, ocean reanalysis, global ocean circulation

1. BACKGROUND

The central goal of the ECCO consortium is the production of global ocean state and parameter estimates in support of climate research. ECCO requires dynamical and kinematical consistency of its products, in particular, conservation of mass, heat, and salt throughout the estimation period. Avoiding shortcomings identified in atmospheric reanalysis (e.g., Bengtsson et al., 2004, 2007) and making optimal use of the sparse observational coverage calls for the use of smoothing methods from optimal estimation theory (Wunsch and Heimbach, 2007, 2013; Stammer et al., 2016). The ECCO method exploits information contained in observations both forward and backward in time, while avoiding unphysical perturbations of the time-evolving state that is being constrained. It is the only method that has been found to be practical and that avoids the shortcomings of reanalyses and combines the very diverse ocean data sets that we now have and will continue to collect. The underlying model serves as a "dynamical interpolator" between and beyond the often sparse and heterogeneously sampled observations (in space and time) of various types.

Among ECCO's early accomplishments was the production of the first generation of near-global ocean state estimates, covering the years 1992–1997 (Stammer et al., 2002, 2004; Stammer, 2003). The latest ECCO solution can be used to produce climatologies, based on most data available from the global observing system since the early 1990s, not only for temperature and salinity, but which also provides consistent three-dimensional flow fields and connected dynamical variables (e.g., sea level and bottom pressure), consistent surface forcing fields, and property budgets to explore the underlying dynamics (e.g., Ekman and Sverdrup transports, mixing, and vorticity fluxes) (Fukumori et al., 2018). Self-consistency among the range of state variables is invaluable for depictions of the global ocean, e.g., in terms of its overturning circulation (Cessi, 2019).

2. THE PRESENT

2.1. The ECCO Central Production

The ECCO estimation framework in production today has undergone a number of significant improvements and updates. Extending over the period 1992–2015 (an update to 2017 is currently under way), the latest product, ECCO version 4 release 3 (ECCOv4, Forget et al., 2015a; Fukumori et al., 2017), has increased horizontal and vertical resolution and covers the entire globe. The estimation framework has been extended to account for uncertain model parameters that are now routinely part of the inversion (Forget et al., 2015b). The production of the next-generation ECCO version 5 at higher spatial resolution is currently ongoing.

Observational data streams have vastly expanded (Fukumori et al., 2017), and the ways in which these are ingested into the estimation framework have been refined. The space-based backbone consists of daily along-track sea level anomalies from satellite altimetry (Forget and Ponte, 2015) relative to a mean dynamic topography (Andersen et al., 2016), monthly ocean bottom pressure anomalies from GRACE mascon solutions (Watkins et al., 2015), monthly sea surface temperature fields from passive microwave radiometry (Reynolds et al., 2002), monthly sea surface salinity fields from Aquarius (Vinogradova et al., 2014), and daily sea ice concentration fields (Peng et al., 2013; Meier et al., 2017). Major *in-situ* observing systems used in ECCO include the global array of Argo floats (Roemmich et al., 2009; Riser et al., 2016), ship-based CTD and XBT hydrographic profiles and gridded monthly climatological temperature and salinity fields from the World Ocean Atlas 2009 (WOA09, Antonov et al., 2010; Locarnini et al., 2010), tagged marine mammals (Roquet et al., 2013; Treasure et al., 2017), and ice-tethered profilers (ITPs) in the Arctic (Krishfield et al., 2008). The versatility of the estimation framework enables the inclusion of novel data sets, such as satellite and *in-situ* inferred electric conductivity as a measure of ocean heat content changes (Trossman and Tyler, 2019). Ocean mixing parameters have been inferred from a subset of Argo, ITP, and hydrographic observations (Cole et al., 2015; Whalen et al., 2015), and are starting to be included in the observational data streams [Trossman et al., in revision].

2.2. Selected Science Applications

Numerous scientific studies have been conducted with various ECCO solutions, leading to new insights into the ocean's role in climate. Partial summaries are in Wunsch et al. (2009), Wunsch and Heimbach (2013), and Fukumori et al. (2018). Here, we highlight two research areas and related studies that have been afforded by the latest ECCO solution. This review only allows for a compressed discussion.

2.2.1. Ocean Heat Content Changes During the Recent Surface Warming Slowdown (SWS) Period

Much attention has been given, both in the scientific literature and in public media to the apparent warming slowdown in global mean surface temperature (GMST) over the first decade of the twenty-first century compared to the 1990s (e.g., Medhaug et al., 2017). The focus on surface temperatures distracted from the fact that a volumetric index such as vertical integrals of heat content changes is a physically more complete climate indicator than (surface) area-based indices. In this context, Nieves et al. (2015) identified issues with several ocean reanalysis products in providing reliable vertical profiles of temperature changes. **Figure 1** shows decadal trends in global mean ocean temperature as a function of depth over the periods 1993–2001, 2002–2010, and the difference between the two, from ECCOv4 and two ocean hydrographies. Decadal difference profiles are not available for Argo, which only reached its global coverage in about 2006. The figure is adapted from Nieves et al. (2015), which did not provide any uncertainty estimates for the hydrographies. Compared to the ocean reanalysis trends analyzed by Nieves et al. (2015), which exhibits large deviations from hydrography, ECCOv4 shows a more credible fit to hydrography trends over much of the depth range 0–1,500 m. ECCO's depicted uncertainty (gray shading) represents the formal standard error computed from a least squares linear trend fit to the monthly ECCO values and scaled to account for the effective degrees of freedom (i.e., residual autocorrelation) assuming the residuals of the fit behave as a first-order autoregressive (AR1) process. Note further that the two hydrographics are markedly different in the upper 800 m. ECCOv4 also reproduces the apparent slowdown in surface temperature trends as compared to an optimally interpolated blend of *in-situ* and satellite SST data. The analysis is set against the larger backdrop of full-depth ocean heat content changes over the last few decades. The latest ECCOv4 estimate produces a global mean heating rate of 0.48 $\pm$ 0.16 W m^{-2}, which includes a 0.095 W m^{-2} geothermal flux (Wunsch, 2018). All uncertainties quoted are likely at lower bounds as they do not account for systematic errors. A full-depth analysis of vertical heat transport by Liang et al. (2017) shows the global mean heat flux imbalances to be small residuals of regionally large anomalies that underly contributions from multiple centers of action, that cooling layers at depths may result from adjustment to surface forcing centuries ago (Gebbie and Huybers, 2019), and the need for accurate budget closure. The use of Argo data since roughly 2006 and satellite altimetric data from 1993 onward in combination with dynamical consistency provides powerful constraints on the ECCO solution over the estimation period.

2.2.2. Origins of North Atlantic Water Mass Volumetric Variability

Quantifying Atlantic water mass variability in terms of its volumetric composition over time provides a powerful diagnostic for determining the relative role of diabatic (locally forced) vs. adiabatic (induced via advection) processes (Forget et al., 2011; Speer and Forget, 2013). An approach is to consider the volume of water contained within temperature classes, following Walin (1982). Such a study has been conducted by Evans et al. (2017) over the period 2004–2011, which

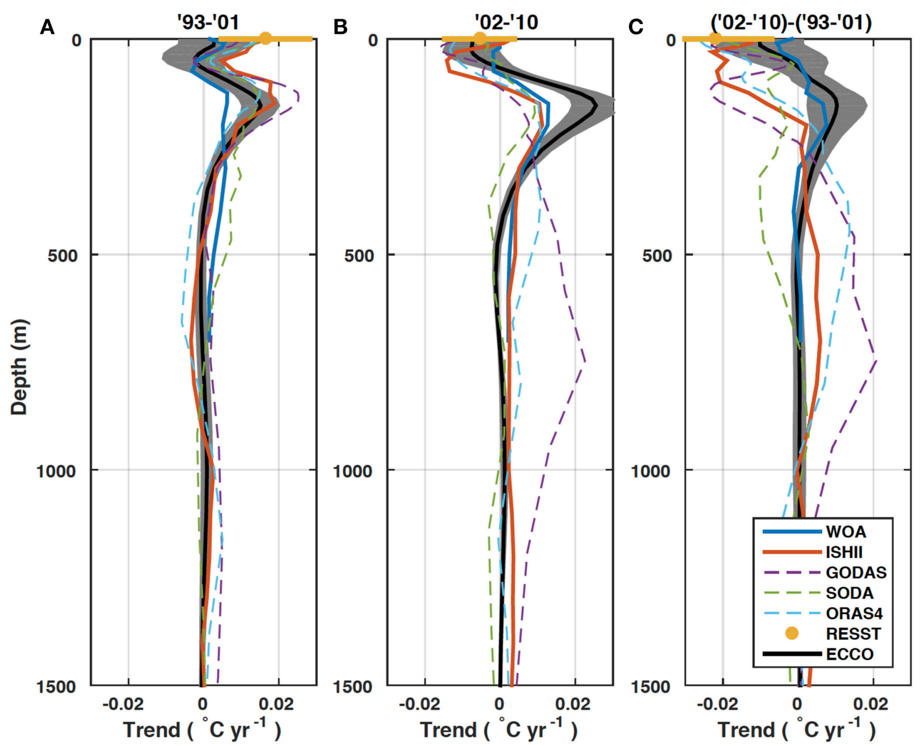

FIGURE 1 | Decadal trends in global mean potential temperature as function of depth over the periods 1993–2001 **(A)**, 2002–2010 **(B)**, and their difference **(C)**, inferred from two hydrographies, three ocean reanalysis and the ECCOv4 state estimate. Black: ECCOv4 (gray shading indicates formal standard error, see main text), dark blue: WOA (Levitus et al., 2012); red: Ishii (Ishii et al., 2005); purple: GODAS (Huang et al., 2010); green: SODA (Carton and Santorelli, 2008); light blue: ORAS4 (Balmaseda et al., 2012); yellow: SST (Reynolds et al., 2002). Adapted from National Academies of Sciences, Engineering, and Medicine (2016) (their Figures 4, 23).

includes the marked reduction in the Atlantic Meridional Overturning Circulation (AMOC) inferred at 26 N from the RAPID mooring array (Roberts et al., 2013). Water mass volume anomalies in temperature classes, $V(\theta, t)$, between 26 and 45 N (**Figure 2**, top panels) were derived from a gridded Argo product (Roemmich-Gilson Argo Climatology, RGAC; Roemmich and Gilson, 2009) and ECCOv4. Both products reflect seasonal exchange of volume between the warmer surface waters ($\theta > 18°$C) and mode/central waters (θ between 10°C and 18°C), as well as interannual variability in volumetric contributions of subtropical mode water ($\theta \sim 18°$C), among others. Determining water mass transformation rates between temperature classes, dV/dt, proves difficult for RGAC (**Figure 2c**), conceivably due to aliasing when sampling the mesoscale eddy field, but is feasible for ECCOv4 (**Figure 2d**). The analysis reveals negative volume anomalies during the winters of 2009/10 and 2010/11. For temperature classes larger than 15°C these anomalies are consistent with diabatic changes inferred from air-sea heat flux diagnostics (**Figure 2e**). However, for temperatures below 15°C, the adiabatic component as diagnosed from ECCOv4 (**Figure 2f**) explains the bulk of the volumetric census anomalies. The study provides compelling evidence that wind-driven transport anomalies led to a southward shift in the mean structure of the interior subtropical gyre circulation, weakening northward volume transport at 26 N. Evidence for the role of such advective signals has previously been gathered across an isolated line of latitude from the RAPID mooring array at 26 N (Cunningham et al., 2013).

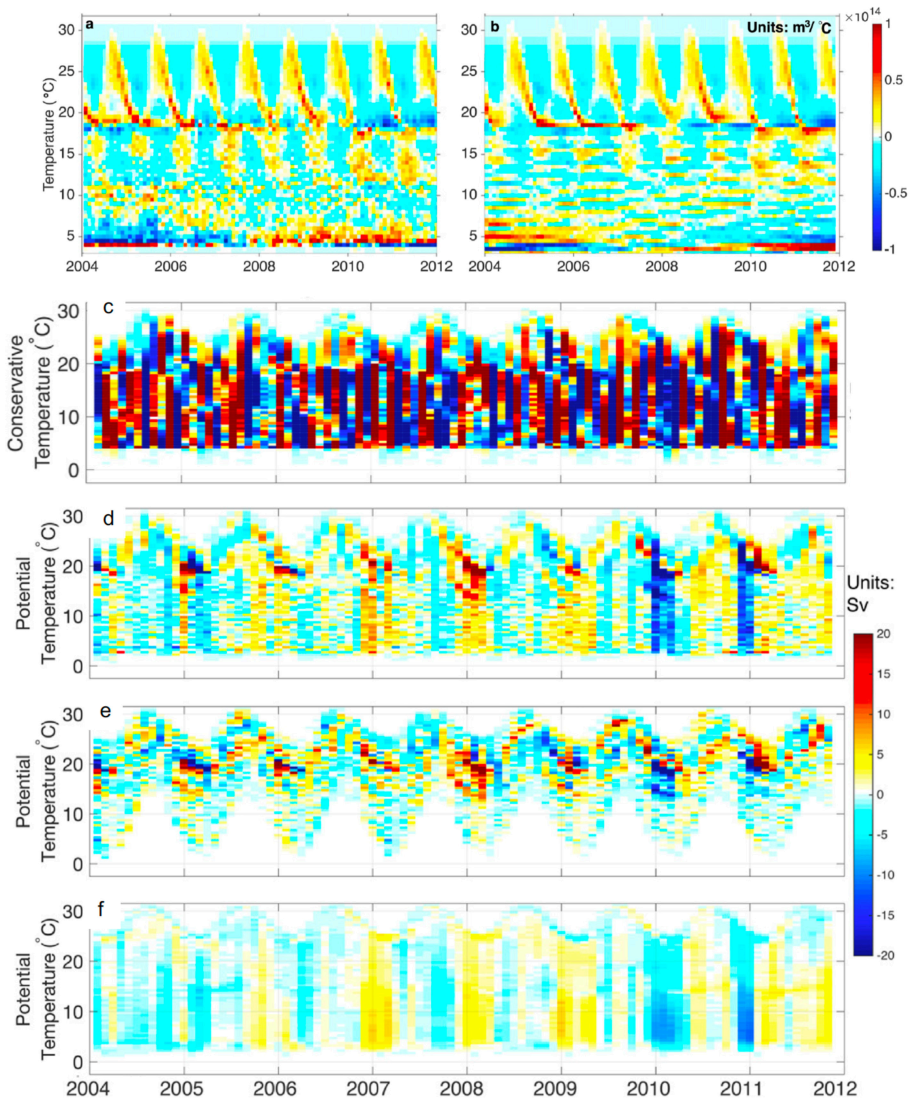

FIGURE 2 | Top panels: Volume anomaly in temperature classes, $V(\theta, t)$, with respect to the time mean in the North Atlantic between 26 and 45 N from **(a)** RGAC and **(b)** ECCOv4. Lower panels: Total monthly dV/dt between 26 and 45 N from **(c)** RGAC and **(d)** ECCOv4. Also shown in **(e)** is the diabatic contribution to **(d)** inferred from monthly diathermal transformation due to air-sea heat fluxes, and **(f)** the adiabatic transformation in **(d)** implied by the volume change per temperature class due transport divergence between 26 and 45 N. For details, see Evans et al. (2017). ©American Meteorological Society. Used with permission.

2.3. Regional and Extended-Period Efforts

The tremendous computational cost involved in conducting the nonlinear least-squares optimization problem as well as the occurrence of strong nonlinearities have so far prevented the production of global eddy-resolving decadal state estimates. Instead, regional eddy-permitting estimates of limited duration have spun-off. These include the Southern Ocean State Estimate (SOSE, Mazloff et al., 2010), the Arctic Subpolar gyre sTate Estimate (ASTE, Nguyen et al., 2017), as well as estimates of the California Current System (Verdy et al., 2014), the tropical Pacific (Hoteit et al., 2010; Verdy et al., 2017), and the Gulf of Mexico (Gopalakrishnan et al., 2013). The versatility of the underlying ECCO infrastructure has facilitated these spin-offs. In turn, experience gained in the regional efforts has benefited the global estimation. Other non-ECCO related regional estimation efforts are summarized by Edwards et al. (2015).

An emerging emphasis has been on coupled ocean-sea ice estimation to account for Arctic and Southern Ocean sea ice. Dedicated efforts to develop a dynamic/thermodynamic sea ice model that fits within the estimation framework (Menemenlis et al., 2005; Heimbach et al., 2010; Losch et al., 2010; Fenty and Heimbach, 2013) led to an initial attempt at the global-scale coupled problem (Fenty et al., 2015). A major focus of ASTE is the finding of data used in Arctic research that are not necessarily part of global data repositories and assessing their use in state estimation (Nguyen et al., 2017). Emerging challenges are the use of satellite observations of sea ice (and snow) thickness, as well as remotely sensed drift data to constrain sea ice velocities.

Restricting estimates to the period with available satellite altimetric data limits the applicability of ECCO products for studies of decadal variability. This issue led to a dedicated effort by the German ECCO (GECCO) partners to extend the estimation period back to 1952 (Köhl and Stammer, 2008). Now in its second generation, GECCO2 has extended the period to cover the entire span of the available NCEP reanalysis, but at the cost of sparse observational coverage to constrain the solution prior to the 1990s. On these long timescales, there are issues with convergence of the optimization, which requires splitting the period into a number of smaller assimilation windows (Köhl, 2014). The challenge of quantifying uncertainties in the estimates that go along with changes in the observing system is exacerbated in the long state estimates.

2.4. Estimation Infrastructure, Data Access and Analysis Tools

A key enabling technology of ECCO is the ability to generate an adjoint version of the Massachusetts Institute of Technology general circulation model (MITgcm) for various configurations by means of algorithmic differentiation (Marotzke et al., 1999; Heimbach et al., 2005). Adjoint code generation via the open-source tool OpenAD (Utke et al., 2008) is being pursued. All ECCO state estimates are free-running solutions to the MITgcm and, as such, can be independently reproduced by users interested in performing new experiments (e.g., ocean response to idealized atmospheric wind stress forcing), determining the impact of new data constraints, and generating problem-specific model output (e.g., tracer dispersion). Extending the existing set of model-data misfit constraints is facilitated by the "generic cost" code framework introduced in ECCO v4. Instructions for re-running the model and complete model configurations (including parameters, initial conditions, atmospheric boundary conditions) are provided alongside the solutions (see **Table 1**).

ECCO products can be accessed via the ECCO webpage (ecco.jpl.nasa.gov). We are currently working to host the standard output fields on NASA's Physical Oceanography Distributed Data Center (PO.DAAC, podaac.jpl.nasa.gov), which will allow users to access the state estimate using several different technologies, including a new secure FTP-like interface (PO.DAAC Drive), Open-source Project for a Network Data Access Protocol (OPeNDAP), Thematic Realtime Environmental Distributed Data Services (THREDDS), and so-called web services enabling access via API protocols. A list of links to data products, model configurations, analysis tools and documentation is summarized in **Table 1** in the *Data Availability Statement* below.

3. THE FUTURE

With the increasing accuracy and skill of the ECCO state estimates, new scientific frontiers come into view. Most of these are related to capturing coupled variability, representing secular changes, and closing property budgets across different

TABLE 1 | Links to ECCO products, configurations, and documentation.

ECCO Products	
Latest product (ECCO v4,r3)	https://ecco.jpl.nasa.gov/products/latest/
All ECCO products	https://ecco.jpl.nasa.gov/products/all/
ECCOv4 release 3 documentation	
User guide (website)	https://ecco.jpl.nasa.gov/products/latest/user-guide/
Evaluating tracer budgets	http://hdl.handle.net/1721.1/111094
Reproduction (on premise or AWS cloud)	https://eccov4.readthedocs.io/en/latest/
Data constraints	http://hdl.handle.net/1721.1/120472
ECCOv4 release 3 analysis tools	
gcmfaces (Matlab)	https://gcmfaces.readthedocs.io/en/latest/
ecco-v4-py (Python)	http://ecco-v4-python-tutorial.readthedocs.io/
xmitgcm (Python)	https://xmitgcm.readthedocs.io/en/latest/
MITgcm (source code)	https://mitgcm.readthedocs.io/en/latest/

components of the Earth system (Buizza et al., 2018). In the following, we sketch several coupled problems that appear on the horizon.

3.1. Increased Horizontal Resolution

An increase in horizontal resolution in future ECCO products is targeted to begin resolving the geostrophic eddy field and its impact on the mean circulation. A drawback is the increased degree of nonlinearity of the underlying estimation problem, and the question over which time period the linearization was implied by the adjoint model remains valid. Possible limitations to long assimilation windows have been raised by Lea et al. (2000) and Köhl and Willebrand (2002), among others. A number of computational and practical solutions in the context of estimating statistical properties rather than nonlinear features ("eddy-fitting") and stabilizing the adjoint to improve controllability at high resolution have been proposed, e.g., by Hoteit et al. (2005), Abarbanel et al. (2010), Wang et al. (2014), and Gebbie and Hsieh (2017). Given the desire within ECCO for maintaining long assimilation windows, i.e. dynamical consistency, these methods are actively being pursued.

3.2. Coupled Ocean-Atmosphere Estimation

A natural extension of ECCO consists in the coupled ocean-atmosphere estimation problem, an avenue pursued by many reanalysis groups today (see Penny et al. [this issue] for a detailed review). Reasons include (i) the ability to close property budgets across the coupled system, (ii) to enable dynamical feedbacks, (iii) to obtain adjusted air-sea fluxes that are consistent with both ocean and atmosphere dynamics, (iv) to infer a coupled state that is balanced with respect to the underlying modeling framework and thus potentially more suitable for initializing extended predictions A major challenge consists in the disparity between oceanic and atmospheric time scales, the time window of validity of the model linearization, which in the atmosphere amounts to synoptic time scales (and in the ocean to resolved eddy turnover time scales), and implications for adjoint model stability for long assimilation windows.

Initial efforts at extending the ECCO capabilities to a fully coupled Earth system model are being conducted using intermediate complexity atmosphere/land models, such as the PlaSim model (Fraedrich et al., 2005; Blessing et al., 2014). This coupled model, called CEN Adjoint Model (CENAM), was put together such that an algorithmic differentiation tool can be used to construct its adjoint for state and parameter estimation purposes. Stammer et al. (2018) present a pilot study for computing adjoint sensitivities of the coupled climate system. To overcome strong nonlinearities, synchronization with observations approaches from dynamical systems theory are being explored to stabilize the adjoint model (Abarbanel et al., 2010; Lyu et al., 2018).

Complementary efforts to understand sensitivities of the ocean to the atmospheric state from a high-end atmospheric model are being conducted in preparation for coupling (Strobach et al., 2018). Other avenues using weak or hybrid coupled assimilation as well as approximate adjoints are also being pursued.

3.3. Coupled Ocean-Ice Sheet Estimation

There is mounting evidence that the increased mass loss from the polar ice sheets, Greenland (WCRP Global Sea Level Budget Group, 2018) and Antarctica (The IMBIE team, 2018), observed over the last two decades is linked to ocean circulation changes that have brought about warmer waters to the grounding zones of marine-terminating glaciers and ice shelves. Concerns over the implications of rising sea levels call for the joint treatment of the coupled ocean-ice sheet system. Substantial progress is being made, both with asynchronous coupling between the MITgcm and the Ice Sheet System Model (ISSM, Seroussi et al., 2017) as well as with synchronous, property-conserving coupling between the MITgcm's ocean and ice stream/shelf model (Goldberg et al., 2018; Jordan et al., 2018). The availability of adjoint models of all of these components, along with at least annually resolved satellite observations at Antarctica's marine margins, offer the prospect of developing a tightly coupled, skillful estimation system.

3.4. Coupled Ocean-Biogeochemistry and Ecology Estimation

The advent of profiling floats equipped with biogeochemical (BGC) sensors presents a revolution in data density for constraining BGC and ecosystem models. The software exists to assimilate these measurements along with remote sensing of ocean color into models (e.g., Gregg et al., 2009; Song et al., 2016; Verdy and Mazloff, 2017). BGC ocean property observations constrain many aspects of the Earth system, such that coupling not only informs the carbon system and ocean health, but also improves many other components of the Earth system models. Another thrust is the development of the ECCO-Darwin project, which combines physical and biological observations with the coupled framework of the eddy-permitting ECCO and Darwin ecosystem models (Follows and Dutkiewicz, 2011), but with significant remaining obstacles (Dutkiewicz et al., 2018).

3.5. Uncertainty Quantification (UQ) and Optimal Observing Network Design

Although formally an integral part of state and parameter estimation, deriving formal uncertainties accompanying the optimal estimates adds another level of computational complexity (National Academies of Sciences, Engineering, and Medicine, 2012). This has so far prevented most ocean reanalysis (or estimation) projects from dealing comprehensively with UQ. In the context of derivative-based estimation, identification of key metrics (or quantities) of interest enables the development of a formal chain that propagates the uncertainties from observations and uncertain parameters (priors) through the inference (i.e., posterior uncertainties at the optimal estimate) to the derived metrics of interest (Kalmikov and Heimbach, 2014, 2018). This Hessian-based framework lends itself to conducting optimal observing system design studies (see Fujii et al., under review) that provide valuable information on the optimal placement of available observational assets to maximize their utility in constraining key oceanographic quantities of interest (Köhl and Stammer, 2004).

3.6. Synergistic Use of Products and Model

While the state estimates are the central product of ECCO estimation, the virtue of their physical consistency is best realized by their analysis in conjunction with the underlying ocean general circulation model. The state estimates provide descriptions of the ocean, whereas the model affords its explanation; e.g., why is the ocean state what it is and why does it change as it does? As experience is gained, application of state estimation is expanding from drawing inferences from sampling the estimates akin to observations to quantitatively analyzing processes by utilizing the complete physics embodied in the model. Examples of such include analyses of property budgets that are closed without unresolved components (e.g., Buckley et al., 2015; Piecuch et al., 2017; Ponte and Piecuch, 2018), tracing origins and fate of ocean water masses (e.g., Fukumori et al., 2004; Gao et al., 2011; Qu et al., 2013) and quantifying causal mechanisms controlling the ocean (e.g., Fukumori et al., 2015; Pillar et al., 2016, 2018; Jones et al., 2018; Smith and Heimbach, 2019). The model's adjoint offers a unique tool in such efforts by providing an efficient means to evaluate physical dependencies among different quantities of interest. While the fidelity of state estimation will continue to evolve, existing systems provide a means to understanding and explaining what they do already resolve of the ocean. The full exploitation of state estimation requires a holistic approach and is ripe for innovation.

4. CONCLUDING REMARKS

The past two decades have seen substantial progress in the development and production of rigorous global ocean state and parameter estimates in support of climate research. That development has relied in part on the availability of continuous climate-quality records of quasi-global coverage, beginning with satellite altimetry (since 1992), satellite gravimetry (since 2003), and hydrographic profiles from the Argo float program (globally since ca. 2006). Sustaining such observing systems over long periods of time to build a climate record is a key imperative of ocean and climate monitoring (National Academies of Sciences, Engineering, and Medicine, 2017). The underlying computational estimation approaches used in the model-data synthesis serve several purposes: (i) they extract optimal information from the sparse and heterogeneous observational streams that constitute the Global Ocean Observing System (GOOS), (ii) they provide a quantitative framework for hypothesis testing and model parameter calibration, and (iii) they enable a quantitative understanding of the underlying dynamical and physical processes that have been learned jointly from observations and models. Much of what these approaches offer, for rigorous climate model calibration and initialization, remains under-explored. Realizing their full potential faces substantial practical hurdles but is indispensable for tackling important issues in ocean climate science. Increasing horizontal resolution and moving toward a comprehensive coupled Earth system estimation framework are major thrusts for the decade ahead.

DATA AVAILABILITY

ECCO strives to make all of its products available online to the scientific community. This includes the state estimates, ancillary fields to perform accurate budget calculations, the complete model configuration to reproduce the state estimate, analysis tools, as well as documentation. **Table 1** provides a comprehensive list of links to these resources.

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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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Synthesis of Ocean Observations Using Data Assimilation for Operational, Real-Time and Reanalysis Systems: A More Complete Picture of the State of the Ocean

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Ocean data assimilation is increasingly recognized as crucial for the accuracy of real-time ocean prediction systems and historical re-analyses. The current status of ocean data assimilation in support of the operational demands of analysis, forecasting and reanalysis is reviewed, focusing on methods currently adopted in operational and real-time prediction systems. Significant challenges associated with the most commonly employed approaches are identified and discussed. Overarching issues faced by ocean data assimilation are also addressed, and important future directions in response to scientific advances, evolving and forthcoming ocean observing systems and the needs of stakeholders and downstream applications are discussed.

Keywords: data assimilation, calculus of variations, Kálmán filters, ensembles, modeling

INTRODUCTION

A cornerstone of all ocean analysis and forecasting efforts is data assimilation (DA; see Carrassi et al., 2018), the rigorous and systematic combination of ocean observations and ocean models that yields an *optimal* estimate of the ocean state (both physical and biogeochemical conditions). The term *optimal* implies that of all possible combinations of the observations and model, it is the resulting *best* estimate that is sought according to some specified criteria. The founding principles of

DA are rooted in Bayes' theorem, the axioms that govern probability (Bayes, 1763), although similar methods arise in the field of control theory (see Talagrand, 2014). In brief, given *a priori* information about the laws governing the ocean state in the form of a model, an *a priori* state estimate from that model, and direct, but incomplete, ocean observations, an *a posteriori* state estimate is computed that weights all available information according to the hypothesized uncertainties in the model and observations. In a Bayesian framework, the *optimal* state estimate is that which coincides with the maximum *a posteriori* probability (Wikle and Berliner, 2007).

While the DA problem can be formulated precisely, the solution is challenging for the vast dimension of the ocean state simulated by operational ocean models that represent many complex non-linear processes. To make the problem tractable, it is necessary to make many simplifying assumptions about, for example, the nature of the *a priori* errors, so that while formally the resulting ocean state estimate is suboptimal, it is nonetheless useful. The most common DA approaches currently employed in operational oceanography are based on either variational or ensemble methods. In the former case, variational calculus is used to identify the ocean state that maximizes the conditional probability of the unknown ocean state given the observations, while for ensemble approaches the evolution of the conditional probability density function is estimated from the observations and an ensemble of plausible ocean states. Both approaches are accompanied by a litany of challenges and shortcomings which are briefly reviewed next.

THE CURRENT STATE-OF-THE-ART OF OCEAN DA

Ocean data assimilation is a mainstay at many operational and academic centers, at both global (*e.g.*, Martin et al., 2015) and regional scales (*e.g.*, Edwards et al., 2015). While the tremendous ongoing efforts of many groups are recognized and acknowledged, individual systems will not be discussed *per se*. The focus instead will be on the general state of the field and ongoing challenges, with a view to the future in the Section "The Future of Ocean DA".

At present, there are two general approaches to ocean DA that serve the needs of different communities. The first approach closely parallels the procedures employed in numerical weather prediction (NWP; see Kalnay, 2003) in which ocean state estimates are computed sequentially through time, and the resulting estimates updated when sufficient new observations become available. Similar methods are also used for producing ocean re-analyses (see Storto et al., unpublished, this issue). However, the continual restarting of the model and ingestion of data means that, in general, the conservation laws of the system may not be continuously respected. This can present a challenge when using the resulting ocean analyses to compute budgets, unless the contribution from the analysis increments is also explicitly included in budget calculations (e.g., Valdivieso et al., 2015; Storto et al., 2017). Thus, an alternative approach can be used in which ocean data are continuously assimilated over a very long (i.e., multi-decade) time-window during which all conservation properties of the ocean are implicitly respected during the model integrations. This latter approach is advantageous for studying the ocean state on climate timescales, although it too presents its own set of challenges (see Heimbach et al., 2019, this issue). That said, the primary focus of this article will be sequential DA methods for operational and real-time applications and historical re-analyses.

As previously noted, two flavors of sequential ocean DA are commonly used at most operational centers, namely variational methods or ensemble approaches. The advantages and shortcomings of each approach will be considered separately followed by a discussion of some overarching challenges common to both.

Variational Methods

Variational (Var) DA can be employed as either 3-dimensional Var (3D-Var) or 4-dimensional Var (4D-Var). During 3D-Var, all data collected within a short time window ($\sim$ days) are assimilated as though collected at a single time. The most recent model forecast during the time window is interpolated to the observation locations close to the observation time, and the observation minus forecast differences (known as the innovations) are used as *prior* information [a procedure referred to as the first-guess at appropriate time (FGAT)]. A variational approach (called 3D-Var FGAT) is used to identify the optimal ocean state assuming that the innovations are valid at one time. In principle, 3D-Var FGAT is relatively straightforward and computationally affordable since only the non-linear forecast model is involved. During 4D-Var, the actual observation times are respected, and measurement information is implicitly interpolated in space and time (over the observation time window) by the governing model equations. Formally the non-linear problem is solved via a sequence of linear approximations involving a linearized version of the forecast model [usually a simplified form of the tangent-linear model (TLM)] and its adjoint (Courtier et al., 1994). As a result, 4D-Var is considerably more demanding than 3D-Var, not only because of the additional computational expense, but also because the TLM and its adjoint must be developed and maintained. However, the TLM and adjoint model have considerable practical utility beyond DA (e.g., Moore et al., 2004).

The first-guess for Var is also commonly referred to as the *background*, and an estimate of the errors in the background is required. A common underlying assumption of Var is that all errors have zero mean (*i.e.*, are unbiased) and are described by Gaussian probability distributions, in which case they are completely characterized by the error covariance matrix. Furthermore, it is assumed that errors in the background and observations are uncorrelated. For some state variables, such as biogeochemical tracer concentrations, the errors are fundamentally non-Gaussian but can be transformed into new variables that are approximately Gaussian (e.g., Simon and Bertino, 2009; Fletcher, 2010).

The error covariance matrices for the background are traditionally denoted as $\mathbf{P}$ (Ide et al., 1997). By necessity, the corrections that the observations make to the first-guess/background must lie in the space spanned by **P** and, as such, **P** has been the subject of much research because of the central role it plays in DA. In basic Var DA, **P** is prescribed at the start of each data assimilation cycle meaning that it is generally only weakly dependent on the background. In some 3D-Var systems, though, flow-dependence is introduced by way of a tensor (Weaver and Courtier, 2001) that spreads innovations along rather than across background field contours, which is particularly desirable in frontal regions where cross- and along-front correlations typically have very different scales. On the other hand, during 4D-Var the TLM and adjoint model implicitly introduce a flow-dependence in the error covariance via the time evolution of the background.

Choosing appropriate forms for **P** and representing them efficiently in a DA system remains one of the most significant and fundamental challenges for variational ocean DA. For example, estimating the actual level of uncertainty of the first-guess is very difficult, and choosing a **P** that accurately reflects the inhomogeneity and anisotropic nature of the errors across the broad range of space- and time-scales that characterize the ocean is challenging, although innovative methods for multi-scale DA are being explored (*e.g.*, Li et al., 2015; Mirouze et al., 2016). Another critical aspect in the specification of **P** is in the transfer of information from the observed variables to other variables, such as spreading information from sea level observations onto the sub-surface. This can be achieved using physically based parameterizations (*e.g.*, Weaver et al., 2005) or using covariance information derived from long model simulations. However, building a database of errors from which **P** can be computed is non-trivial, and usual approaches rely on anomalies with respect to means, ensemble anomalies, or lagged forecast differences.

While experience at some NWP centers has demonstrated superior performance of 4D-Var relative to 3D-Var (*e.g.*, Lorenc and Jardak, 2018) the cost-versus-benefit of the two approaches is still an open question for the ocean. Traditional 4D-Var methods are iterative sequential algorithms and are not readily parallelizable in time on modern computer architectures since each iteration depends on the previous iterations. Ensemble methods, discussed next, are free of this limitation, although parallel approaches to 4D-Var are being developed (*e.g.*, D'Amore et al., 2014; Fisher et al., 2016).

Ensemble Methods

The sequential DA problem can also be formally solved in the form of the Kálmán-Bucy Filter (KF). However, the large dimension of the system prohibits use of the KF as originally formulated because of the need to evolve the error covariance matrix **P** in time. A practical solution to this problem is to use an ensemble approach (akin to a Monte Carlo method) to approximate **P**. The literature abounds with many flavors of ensemble-based KFs (EnKF; Houtekamer and Zhang, 2016) in which a standard feature is an ensemble of non-linear model solutions that reflect the distribution of the errors in the first-guess ocean state resulting from uncertainties in the model inputs and physics. Ensemble generation is by no means a trivial undertaking, however, and care must be exercised when creating an ensemble. Since each ensemble member will typically require a run of the forecast model, the size of the resulting ensemble will usually be much smaller than the dimension of the system. As such, *covariance localization* and *covariance inflation* are essential ingredients of any practical EnKF.

Covariance localization is a procedure employed to eliminate spurious covariances arising from the limited size of the ensemble. The method involves applying a point-wise weighting ("localization") function to the ensemble-derived **P** which can be a costly procedure. Furthermore, localization can degrade the dynamical consistency of the computed analyses (e.g., Cummings, 2005; Oke et al., 2007), and subsequent forecast. Nevertheless, localization can be useful when accounting for the wide range of circulation scales by using scale-dependent localization functions (*e.g.,* Buehner and Shlyaeva, 2015). The limited size of the ensemble can also lead to an underestimate of the true covariance **P**, and sophisticated methods for inflating the covariance have been developed to address this problem (*e.g.*, Anderson, 2009).

For some applications, the computational cost of an EnKF can be prohibitive, so less-optimal and more practical approaches, such as ensemble optimal interpolation (EnOI; that uses a time-invariant ensemble to estimate **P**), are sometimes used (Oke et al., 2002; Evensen, 2003; Sakov and Sandery, 2015). Other simplified EnKF approaches include using the leading eigenvectors of **P** (e.g., Brasseur and Verron, 2006; Lellouche et al., 2013).

While there is still debate about the minimum required ensemble size for ocean applications, the EnKF is attractive because, like 3D-Var, only the non-linear forecast model is needed, and the ensemble generation is highly parallelizable, which is an additional appeal for operational applications. The ensemble also provides information about uncertainty in the forecasts which can be useful for downstream applications.

Observation Streams and Observation Errors

Real-time data streams are obviously a critical component of any operational ocean DA system, and include satellite remote sensing observations in the form of sea surface temperature, sea surface height, sea surface salinity, and ocean color. Additional remotely sensed observations of surface currents from coastal high-frequency radars are another important source of data in regional systems. Critical subsurface hydrographic information is provided by profiling Argo floats, permanent mooring arrays (*e.g.,* TAO/TRITON, PIRATA, and RAMA), and CTD and XBT measurements from research vessels, ships of opportunity and tagged marine mammals. Observations from autonomous vehicles and ocean gliders have also become an important data source in recent years. However, regardless of the data stream, quality control is also a critical component of DA.

A significant challenge for ocean DA is characterization of observation errors described by the observation error covariance matrix, **R**. In addition to instrument errors, **R** also formally includes the influence of errors due to interpolation of the model fields to the observation points, as well as errors associated with the inability of the model to represent all of the processes captured by an observation. The latter is probably the most significant contributor to **R** and is perhaps the least well understood (e.g., Oke and Sakov, 2008). Furthermore, quantifying and accounting for spatial and temporal correlations in satellite observation errors is a challenge, but can have a significant impact on the ocean state estimate (Chabot et al., 2015). Not accounting for such correlations therefore can also significantly limit the capabilities of ocean DA to capitalize fully on the dense observations that are now available from many different platforms.

In modern DA systems, the impact of each observing platform on the analyses and forecasts can be quantified and continuously monitored. This can provide valuable feedback to instrument operators in cases where platform impacts systematically drift from the norm and become outliers. Such quantitative information can also help government agencies lobby for resources to maintain or expand existing high impact observing systems.

Overarching Challenges for Ocean DA

While variational and ensemble DA methods present their own particular difficulties, some challenges transcend both approaches. For instance, model error is a significant limiting factor in *all* DA systems. Sources of model error include numerical approximations due to constraints on grid resolution and the limitations of parameterizations of important physical and biogeochemical processes. While model errors can be formally accounted for during DA (Bennett, 2002), specification of the model error covariance matrix is a major challenge. Surface and lateral boundary condition errors also represent a significant source of error, particularly at open boundaries in regional models.

Another significant obstacle for many ocean DA systems is systematic errors in the form of bias, which violates the fundamental assumption that underpins current approaches to DA. Sources of bias include model error and boundary condition error. While bias-correction techniques are currently employed at some centers in an attempt to minimize the impact of model error (*e.g.*, Balmaseda et al., 2007), ultimately the root-cause of systematic error must be identified and eliminated. Observation bias is also an issue (particularly in satellite observations due to instrument differences), and care must be taken to account for bias either before or during the DA process (*e.g.*, Lea et al., 2008; While and Martin, unpublished). As coupled Earth system modeling becomes the new norm, the need for DA methods that can simultaneously estimate the systematic model bias and the time-evolving model state will need to be addressed. In uncoupled systems, such model biases have traditionally been attributed to errors in atmospheric forcing. However, such a one-sided view will not be possible in Earth system models where the forecast must satisfy the initial constraints and model equations of all components.

More often than not, DA upsets the dynamical balances in the model, and the ensuing readjustment of the system can introduce unrealistic and intermittent levels of wave energy. This long-standing and ubiquitous problem is referred to as "initialization shock" and has received much attention in NWP where its effect on a forecast can be calamitous if left unchecked. In ocean DA it has received much less attention, although many centers apply *ad-hoc* techniques [such as Incremental Analysis Updates (IAU)] to mitigate the problem. However, the ensuing ocean wave activity resulting from initialization shocks can be especially pernicious for some applications, such as biogeochemical modeling (*e.g.*, Raghukumar et al., 2015; Waters et al., 2017).

THE FUTURE OF OCEAN DA

There are many exciting new directions and future opportunities for discovery in ocean DA. Perhaps the most immediate development borrowed from NWP is the merger of ensemble and variational methods that draws on the strengths of both approaches. Specifically, the static estimate of **P** used in Var and the flow-dependent estimate of **P** from an ensemble are combined to form a "hybrid" **P** that is employed in a DA system (*e.g.*, Lorenc et al., 2015). In this way, the dynamical interpolation properties of the adjoint and the flow-dependent covariance information from the ensemble are simultaneously exploited. Experience in NWP suggests that the performance of hybrid approaches can improve the performance of an analysis-forecast system (Lorenc and Jardak, 2018), and efforts are underway to develop similar procedures for global (*e.g.*, Penny et al., 2015; Frolov et al., 2016; Storto et al., 2018) and regional (*e.g.*, Oddo et al., 2016) ocean prediction systems.

DA analysis and re-analysis products at higher horizontal and vertical resolution will continue to be a priority and a challenge. As such, the need for regional DA systems will likely increase, either stand-alone or embedded in global or other regional models. Therefore, the development of DA capabilities in nested models is an important and emerging research area.

While DA in coupled Earth system models is a high priority (see Penny et al., unpublished, this issue), DA in coupled sub-component models is also of considerable interest. For example, DA in ocean-sea-ice models (*e.g.*, Buehner et al., 2017), physical-biogeochemical ocean models (Fennel et al., unpublished) and acoustic-physical models (Lermusiaux and Chiu, 2002) targets pressing environmental and operational concerns.

Various community DA resources are being developed, such as the Data Assimilation Research Testbed (DART; Anderson et al., 2009), the Object-Oriented Prediction System (OOPS), the Joint Effort for Data assimilation Integration (JEDI), EnKF-C (Sakov, 2014), and the Parallel Data Assimilation Framework (PDAF; Nerger and Hiller, 2013). These are likely to play a more significant role in the development of existing and new ocean DA capabilities. Since the development of DA systems requires a considerable investment of time and resources, community resources such as these will be vital for streamlining the process.

The development of DA methods that do not rely on the assumption of unbiased, Gaussian distributed errors (such as particle filters, van Leeuwen et al., 2015) is also actively being pursued to deal, for example, with the typically non-Gaussian distribution of biogeochemical variables in coupled physical-biological systems.

Responding to new and emerging observing platforms is also a crucial ongoing endeavor in ocean DA. For example, the planned launch in 2021 of the Surface Water and Ocean Topography (SWOT) mission promises to deliver an unprecedented level of detail about the ocean topography, and ocean DA systems must be ready to make efficient use of this new data stream (*e.g.*, Carrier et al., 2016). SWOT will also usher in DA at the ocean sub-mesoscale (∼0.1 to ∼10 km), and considerably enhance the utility of high-resolution satellite radiometers and rapid sampling *in situ* probes deployed on ocean gliders and AUVs. Satellite-derived surface salinity also lends support to other observations currently assimilated by most operational systems (*e.g.*, Toyoda et al., 2015; Martin et al., 2019), and there is a need for concomitant physical and biogeochemical measurements in support of coupled physical-biogeochemical DA to ensure consistency between the different fields. Finally, DA-based tools for designing adaptive sampling arrays are also emerging, heralding a new era of model-informed ocean observing systems.

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Time of Emergence of Surface Ocean Carbon Dioxide Trends in the North American Coastal Margins in Support of Ocean Acidification Observing System Design

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Time of Emergence (ToE) is the time when a signal emerges from the noise of natural variability. Commonly used in climate science for the detection of anthropogenic forcing, this concept has recently been applied to geochemical variables, to assess the emerging times of anthropogenic ocean acidification (OA), mostly in the open ocean using global climate and Earth System Models. Yet studies of OA variables are scarce within costal margins, due to limited multidecadal time-series observations of carbon parameters. ToE provides important information for decision making regarding the strategic configuration of observing assets, to ensure they are optimally positioned either for signal detection and/or process elicitation and to identify the most suitable variables in discerning OA-related changes. Herein, we present a short overview of ToE estimates on an OA variable, CO_2 fugacity $f(CO_{2,sw})$, in the North American ocean margins, using coastal data from the Surface Ocean CO_2 Atlas (SOCAT) V5. ToE suggests an average theoretical timeframe for an OA signal to emerge, of 23(±13) years, but with considerable spatial variability. Most coastal areas are experiencing additional secular and/or multi-decadal forcing(s) that modifies the OA signal, and such forcing may not be sufficiently resolved by current observations. We provide recommendations, which will help scientists and decision makers design and implement OA monitoring systems in the next decade, to address the objectives of OceanObs19 (http://www.oceanobs19.net) in support of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) (https://en.unesco.org/ocean-decade) and the Sustainable Development Goal (SDG) 14.3 (https://sustainabledevelopment.un.org/sdg14) target to "*Minimize and address the impacts of OA*."

Keywords: ocean acidification, CO_2 fugacity, time of emergence, climate change, novel statistical approaches, observing system optimization, decision making tool

INTRODUCTION

Time of Emergence (ToE) is a term that describes the time when a secular signal emerges from stochastic natural variability. There are two main motivations for determining ToE of ocean observations (Rodgers et al., 2015): to identify when a secular trend unfolding within a marine ecosystem may become evident, relative to the natural background variability, and to inform strategic development of ocean observing systems, purposed for the detection of a secular signal. As a quantitative measure, ToE is a valuable metric to consider asset prioritization in concert with active dialogs with the community of researchers and data users.

Previous studies addressing the concept of emergence [ToE or year of emergence (YoE)] have mostly focused on climate and open ocean variables, such as temperature (Hawkins and Sutton, 2012), precipitation (Mahlstein et al., 2012), and sea levels (Lyu et al., 2014). More recently, ToE has also been investigated for trend signals in ocean biogeochemical variables including key ocean acidification (OA) indicators, mostly for the open ocean using Earth System Models (ESMs) (Ilyina et al., 2009; Friedrich et al., 2012; Christian, 2014; Keller et al., 2014; Rodgers et al., 2015; Carter et al., 2016; Frölicher et al., 2016; McKinley et al., 2016; Henson et al., 2016, 2017; Heinze et al., 2018). These ESM studies have shown that: OA variables experience shorter ToE than most other Essential Ocean Variables (EOVs), such as dissolved organic carbon (DOC) and the biodiversity and ecosystem EOVs (Miloslavich et al., 2018) due to their relatively lower natural variability and stronger non-linear trend in response to anthropogenic forcing; ToE has substantial spatial variability and some studies report relatively shorter ToE in low and high latitudes (Henson et al., 2016, 2017), while others indicate the opposite (Keller et al., 2014); ToE may be more sensitive to stochastic background variability rather than the signal trend strength. Some ocean time-series sites are long enough to detect anthropogenic forcing in ocean biogeochemical variables such as CO_2 fugacity $f(CO_{2,sw})$ and pH, apart from natural variabilities (Henson et al., 2016; Bates, 2017). In other systems (e.g., Gulf of Maine Vandemark et al., 2011; Salisbury and Jönsson, 2018), however, detection of OA from atmospheric CO_2 invasion, is complicated by the influence of other factors, such as freshwater input, organic matter cycling, and ocean circulation (Ilyina et al., 2009; Carter et al., 2016).

In the coastal ocean, the estimates of ToE are challenging due to substantially higher variability of OA variables, such as pH (Hofmann et al., 2011; Duarte et al., 2013) and $f(CO_{2,sw})$ (Frankignoulle and Borges, 2001; Dai et al., 2009; Guo et al., 2009; Huang et al., 2015), as well as insufficient temporal duration of coastal time-series. The coastal systems are also not suitably resolved in global models to provide reliable ToE estimates. Assuming the anthropogenic forcing is similar in magnitude and direction as in the open ocean, large variability in the coastal ocean should lead to significantly longer ToEs. Kapsenberg and Hofmann (2016) adopted the pH trend value for the North Pacific (Dore et al., 2009; Ishii et al., 2011) and estimated ToE for pH at Anacapa Island (40 years) to be more than triple the time it takes to detect OA trends in the open ocean (Keller et al., 2014). In comparison, for some coastal locations (e.g., Tatoosh Island, WA, United States), trends may be detected sooner (Wootton and Pfister, 2012). Sutton et al. (2018) used the autonomous moored surface ocean pCO_2 and pH data to derive ToE estimates, suggesting that the time necessary to detect an anthropogenic trend in seawater pCO_2 and pH varies from 8 to 15 years at the open ocean sites, in contrast to coastal sites where estimates ranged from 16 to 41 years.

Several other studies have provided observation-based trend estimates of OA variables for coastal time-series stations or data-driven regional analysis (Wang et al., 2016; Reimer et al., 2017; Wang et al., 2017; Laruelle et al., 2018 and references therein). Using a new statistical approach Generalized Additive Mixed Modeling (GAMM) Wang et al. (2016, 2017) detected multidecadal sea surface $f(CO_{2,sw})$ trends at a $1° \times 1°$ resolution. They reported that the sea surface $f(CO_{2,sw})$ trends on decadal time scales in the Northern Hemisphere (1.93 ± 1.59 μatm year^{-1}) closely follow the atmospheric fCO_2 increase rate (1.90 ± 0.06 μatm year^{-1}) but appear slower in the Southern Hemisphere (1.35 ± 0.55 μatm year^{-1}). In addition, they also observed differences between western and eastern boundary current-influenced areas. Laruelle et al. (2018) used wintertime data only and investigated the rate of change in air–sea CO_2 gradients in continental shelves and nearby upper slopes. Consistent with previous studies, they found that surface water pCO_2 closely tracks the rate of atmospheric increase in some coastal margins, while other areas have significantly lower or even negative trends as a result of eutrophication (e.g., Baltic Sea) and/or rapid exchange with the open ocean (South Atlantic Bight). Such negative trends may complicate the ToE analysis, as drivers for negative trends [such as gradual changes in precipitation, freshwater input, and net ecosystem production which all could decrease $f(CO_{2,sw})$] are challenging to predict on the multidecadal timescale. Therefore, reliably estimating secular trends for the OA variables in coastal regions still remains a great challenge, due to limited spatiotemporal observations relative to the inherent large natural variability of these systems.

Herein, we provide ToE estimates of a variable useful in the detection of OA and related to the inorganic carbon EOV sub-variable pCO_2, $f(CO_{2,sw})$, in the North American ocean margins. These estimates are based on both "forced" and "observed" trends, where the latter is calculated using the statistical approach from Wang et al. (2016). The adoption of forced trends allows us to examine whether it is even theoretically possible to detect a long-term $f(CO_{2,sw})$ increase due to atmospheric CO_2 invasion amongst natural variability within a suitable timeframe. The comparison between ToEs obtained using the forced and observed trends will help to assess if such trends, based on currently available data, are statistically robust to detect OA or if the signal is muted, masked, or amplified by other forcing(s) that may also be secular and/or oscillating in nature. Regions, identified as departing from the forced OA trends, likely represent areas where discrimination of various contributing forcings needs to be performed before specific attribution of OA can be discerned. The goal of this exercise is to provide strategic information on the most suitable locations for deployment or augmentation of further multidecadal sustained time-series observatories primarily purposed for the detection of an anthropogenic OA signal (ToE <20 years). At time-series observatories with longer ToE (>20 years), the local variability would limit such application without careful discrimination of other processes that affect observed trends. Such locations may, however, represent high priority science sites for other processes. Our approach provides one example of a tool that can be used to aid the prioritization of observation system investments and optimal utilization of resources in the next decade, contributing to the goals of OceanObs19.

DATA AND METHODS

ToE is defined as:

$$\text{ToE} = (\text{N} \times \text{noise})/\text{trend} \quad (1)$$

where noise (μatm) is a measure for natural variability, and N is a specified threshold (weighting coefficient) that characterizes when the "signal" of anthropogenic climate change exceeds the "noise" of natural variability. In past studies, N has been somewhat arbitrarily chosen (as 1, 2, and 3), with 2 used in most studies (Sutton et al., 2018). We also adopt $N = 2$ for this exercise. ToE calculation depends on reliable estimates of both noise and trends. Noise is commonly defined as the standard deviation (SD) of a temporally detrended time-series, which removes the long-term change (temporal trend × time period). Temporal trends can be calculated over different timescales with a variety of approaches, such as linear least square regression, Markov Chain Monte Carlo (MCMC) method (Majkut et al., 2014), GAMM (see above), and the neural network approach (Landschützer et al., 2013). While temporal trends can be obtained using the actual observational data (Wang et al., 2016, 2017), some studies adopt a "forced" atmospheric CO_2 trend for ToE estimates [e.g., the difference between a constant atmospheric CO_2 at Year 1850 condition and an increasing atmospheric CO_2 (McKinley et al., 2016), or 2 ppm year^{-1} (Sutton et al., 2018)]. ToE, calculated with the forced trend (ToE_{forced}), represent the timescales for the anthropogenic CO_2 signal, only to become detectable out of internal variability (McKinley et al., 2016) assuming no other secular forcing trends are acting on the system. However, it may be different from the calculated ToE based on observed trends (ToE_{obs}), given that many other processes in addition to atmospheric CO_2 forcing may affect the ocean margins (Fennel et al., 2018).

To better understand the combined effect from both atmospheric CO_2 increase and other forcing, we calculated both ToE_{forced} and ToE_{obs} for $f(\text{CO}_{2,sw})$ in all 0.5° × 0.5° grids in the North American coastal margins using SOCAT coastal data V5 (Bakker et al., 2016) and the GAMM method. Note that "coastal" is defined as less than 400 km from the coastline, and the data covered the area between 30°S and 70°N. The oceanic CO_2 data collection clearly had monthly bias (with only 85 out of 1341 grids having relatively homogenous monthly samplings). To compensate for the sampling bias, a spline fitting of all de-trended annual data was used to remove seasonal fluctuations in the time-series data in each grid (Wang et al., 2016). The 0.5° × 0.5° grids for ToE calculations were selected based on the following criteria: (1) have at least a 10-year record; (2) half of the years during the entire time span have data; and (3) have at least six different months of data collection in each grid. For example, a grid that has a 20-year time span will be included in our analysis only if there are at least ten different years and six different months of data coverage. Nevertheless, the majority of grids have more than 10 months of data, which satisfied the requirements. Outliers were defined as any $f(\text{CO}_{2,sw})$ value falling outside of the 1.5 times interquartile range. These outliers were also excluded from the analysis.

The long-term observed $f(\text{CO}_{2,sw})$ trend was calculated in each selected grid using the GAMM method as described in Wang et al. (2016). Briefly, the GAMM method predicts $f(\text{CO}_{2,sw})$ primarily based on three terms derived from observations: seasonal cycle, environmental covariates (temperature and salinity), and the long-term $f(\text{CO}_{2,sw})$ change. The coefficient of the long-term change represents the $f(\text{CO}_{2,sw})$ trend during the examined time span. We identified 438 grids with significant "observed" $f(\text{CO}_{2,sw})$ trends ($p < 0.05$) from 1478 grids in North American coastal margins, and 39 of these 438 grids had negative values. For each of these 438 grids, the long-term change was removed from the original dataset to create the detrended dataset, which was then used to calculate the standard deviation of the detrended time series ($\text{SD}_{detrended}$). ToE_{obs} was calculated using Eq. 1, as 2 × $\text{SD}_{detrended}$/trend. ToE_{forced} was calculated for the same selected grids using Eq. 1 and the forced $f(\text{CO}_{2,sw})$ trend of 2 μatm year^{-1}.

Note that the trends observed may be different from the anthropogenic CO_2 (forced) trend because of the presence or absence of other processes (e.g., upwelling or terrestrial nutrient input). The challenge, however, is to determine whether the observed trend will persist at a constant rate in the future, or if changes in the contribution of the other forcing processes may vary over time.

RESULTS AND DISCUSSION

Spatial Distribution of $\text{ToE}_{\text{forced}}$ and ToE_{obs}

The average ToE_{obs} of $f(\text{CO}_{2,\text{sw}})$ in the North American coastal margin surface waters (excluding grids with the negative values) is 28.7 ± 20.4 years and significantly ($p << 0.0001$) longer than the average $\text{ToE}_{\text{forced}}$ 23.0 ± 13.1 years, implying that coastal processes are likely obscuring the signal attributed to the atmospheric CO_2 forcing and making it harder to observe. Both $\text{ToE}_{\text{forced}}$ (**Figure 1**) and ToE_{obs} (**Figure 2**) show high spatial variability but similar spatial patterns with greater values along the east coast (30.7 ± 22.9 years) than in the west coast (23.7 ± 15.4 years), suggesting that observing systems deployed along the Pacific coast will detect the OA signal earlier than other U.S. coastal margins. Relatively larger absolute values of ToE_{obs} in the east coast were partly attributed to higher variability ($\text{SD}_{\text{detrended}}$), as the average observed trends were similar for both coasts (1.85∼1.88 μatm year^{-1}). However, other decadal trends may play a role, for example warming, salinity

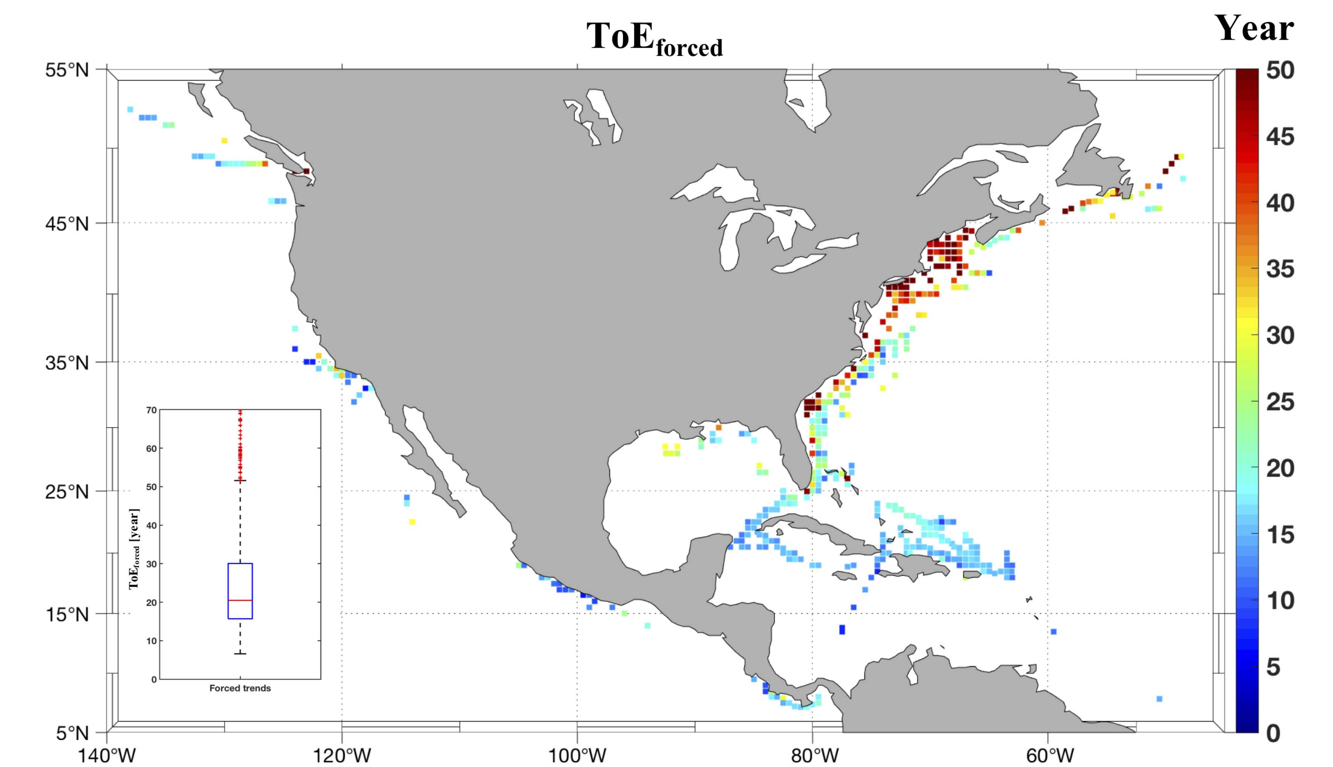

FIGURE 1 | ToE_{forced} of $f(CO_{2,sw})$ in the North American coastal margins. The inserted panel is the boxplot of ToE [the red line inside the blue rectangle (the interquartile range) represents the median, the "whiskers" above and below the rectangle show the minimum and maximum ToE values, and the red crosses are the outliers].

changes and enhanced primary productivity act antagonistically to mask the OA signal in the Gulf of Maine and other northeast regions (Salisbury and Jönsson, 2018), and increased upwelling acts synergistically with OA to amplify the observed trend in the west coast (Fennel et al., 2018 and references therein). The area south of 40°N along the west coast, featured exceptionally short ToE based on both observed and forced trends. For example, the ToE_{obs} in California upwelling areas (17.8 ± 9.1 years) was shorter than other areas, because of low $SD_{detrended}$ (17.8 ± 8.8 μatm). In contrast, in some other areas, such as the Caribbean Sea, the observed trends (1.5 ± 0.4 μatm year^{-1}) were substantially slower than forced trends, which results in a ToE_{obs} almost 6 years longer than would be assumed by OA alone (ToE_{obs} = 21.9 ± 9.6 years versus ToE_{forced} = 16.1 ± 4.0 years). Furthermore, the 39 grids with negative trends are mainly in the Gulf of Maine, along the Gulf Stream and in the northern Gulf of Mexico. In the Northeast U.S. Continental Shelf and Scotian Shelf, such a decrease in surface CO_2 may be due to higher biological uptake as indicated by about 50% increase in surface chlorophyll concentration from 1998 to 2017 (O'Brien, 2018). In the Gulf of Mexico, there were limited data in the current SOCAT database, so a better understanding may be achieved using future iterations that include additional data. It is worth remembering that the calculated ToE_{forced} in these negative CO_2 trends areas only represent a theoretical period, when the anthropogenic CO_2 increases outpace the natural variability, assuming that the drivers are not changing. If the increase of biological uptake of carbon outpaces OA in the Gulf of Maine, as suggested by chlorophyll concentration increasing over the last decade, the OA signal may remain masked.

ToE in the Coastal Margins vs. Open Ocean

In agreement with previous estimates of ToE of OA variables in costal margins (Sutton et al., 2018), our results suggest that the average ToE of surface $f(CO_{2,sw})$ in ocean margins is greater (>20 years) than in the open ocean. Ocean margins are subjected to multiple forcings that can confound the $f(CO_{2,sw})$ increase caused by atmospheric CO_2 accumulation alone and therefore a longer time-series observation may be needed to detect the OA in comparison to the open ocean, unless efforts are made to deconvolute the various contributing processes. Nevertheless, ToE for $f(CO_{2,sw})$ is shorter than that for SST (80.4 ± 49.4 years), consistent with previous studies in the open ocean (Christian, 2014; Keller et al., 2014; Rodgers et al., 2015; Henson et al., 2016, 2017). This is not surprising, considering that CO_2/OA are being directly forced anthropogenically through increasing atmospheric CO_2 concentrations (past centuries), changes in physical oceanographic forcing such as upwelling (recent decades), or nutrient increase (recent decades). SST instead reacts

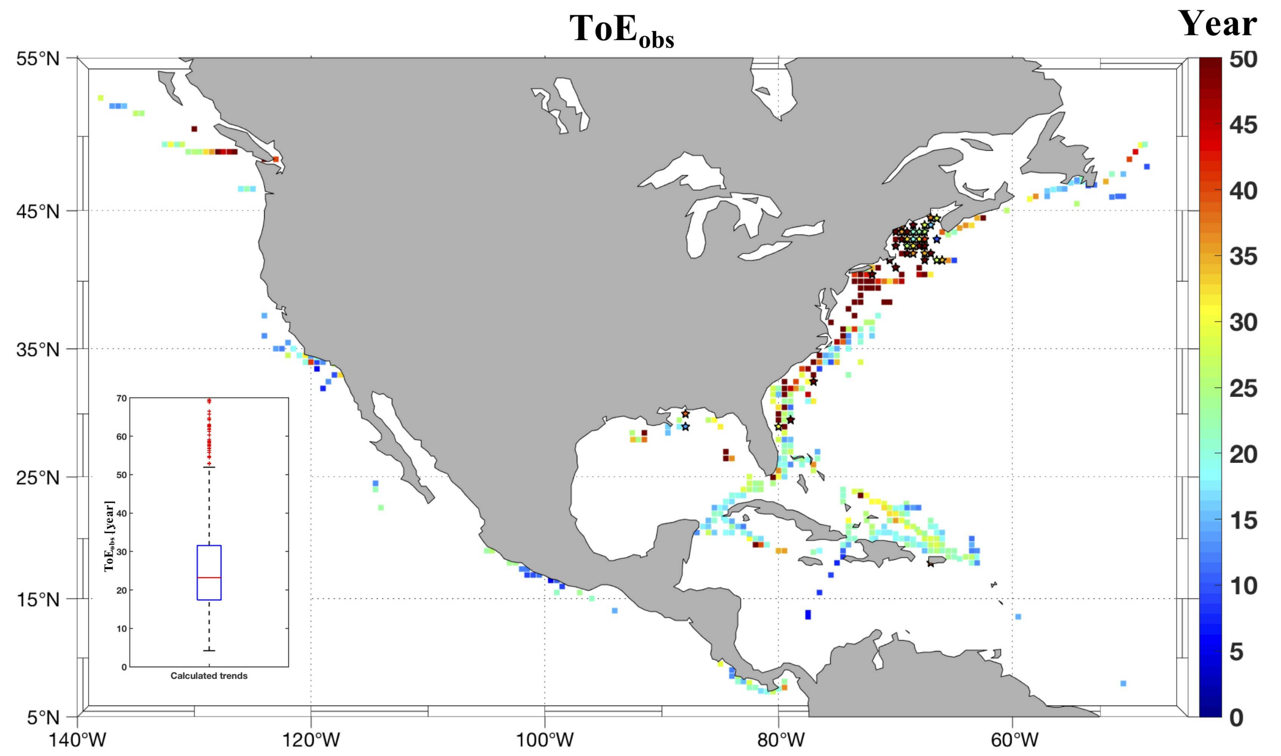

FIGURE 2 | ToE_{obs} of $f(CO_{2,sw})$ in the North American coastal margins. Note, the pentagram symbols highlight the negative trends, and the corresponding ToE represents the absolute value. The inserted panel is the boxplot of ToE [the red line inside the blue rectangle (the interquartile range) represents the median, the "whiskers" above and below the rectangle show the minimum and maximum ToE values, and the red crosses are the outliers].

to the CO_2 increase induced by climate change, and thus the magnitude of the trend signal will be smaller (Keller et al., 2014).

MAIN FINDINGS AND RECOMMENDATIONS

Main Findings

- Based on data currently included in SOCAT V5 coastal database and assuming a forced trend, the theoretical timeframe (ToE_{forced}) within which the OA signal in $f(CO_{2,sw})$ will emerge in the North American coastal margins, is 23 ± 13 years on average. This result should be interpreted as an ideal case, whereby the secular trend is solely driven by atmospheric CO_2 invasion amid natural background variability. However, there is considerable fine-scale spatial variability with significantly lower values (<20 years) along the west coast and the Caribbean Sea, while it may take east coast waters 30 years or longer to express OA conditions outside natural variability.
- Less than 30% of the grids provided significant observed $f(CO_{2,sw})$ trends, primarily reflecting gaps in the current SOCAT database, or data records of insufficient length, to exhibit the trend. ToE based on these observed trends (ToE_{obs}) was on average 5 years longer than ToE_{forced}, implying that most coastal areas are experiencing antagonistic secular and/or multi-decadal forcing that dampen the OA signal (notable exceptions are apparent).
- Overall, both ToE_{obs} and ToE_{forced} of surface $f(CO_{2,sw})$ in the North American ocean margins (23 ± 13 and 28.7 ± 20.4 years, respectively) are higher than that in the open ocean (<20 years). Large regional differences suggest the influence of long-term non-OA processes (e.g., warming, eutrophication, enhanced primary productivity, and increased upwelling) that may not be sufficiently resolved by current observations.

Recommendations

- ToE_{forced} and ToE_{obs} values suggest that locations along North American west coast will likely express an anthropogenic OA signal sooner, and therefore are suitable places for OA signal detection in the next few decades. At east coast locations with longer ToEs, other forcings may counteract $f(CO_{2,sw})$ change. Continuation of time-series observations, which include a comprehensive suite of measurements and/or coupled with targeted process investigations that allow for specific discrimination of the different forcing processes, is needed at these locations to better assess if the observed trends persist and better discern the OA signal.
- In many instances, we cannot expect that the OA signal is currently detectable directly from observing assets. Longer

coastal time-series and the integration of multidisciplinary data from SOCAT, Global Ocean Data Analysis Project (GLODAP), Volunteer Observing Ship (VOS), *in situ* moorings and remote sensing are needed to provide better estimates of ToE_{obs} for $f(CO_{2,sw})$ and other OA variables (pH and aragonite saturation states), in order to develop proxies of ToE in areas of limited observations. Closer collaborations between multidisciplinary time-series programs and modelers, who use the observations and coastal modeling that more comprehensively account for the range of coastal biogeochemical processes, are also urgently needed to support decision making tools.

- Further review of methodology for the calculation of trends and variability, to address challenges such as seasonal sampling bias, original vs. detrended data, and use of arbitrary specified threshold (N), is needed. N represents a qualitative assessment of when we suspect the environment experienced by the marine organisms is "noticeably" different. N is most likely species dependent and may vary between different regions, especially if vulnerabilities of organisms are taken into consideration. Studies that will provide better estimates of what a meaningful threshold might be for a specified application are therefore needed. Defining best practices for calculating ToE and standardization of OA measurements is recommended.
- A similar ToE analysis as presented here is recommended for other EOVs in support of designing a new multi-purpose (beyond OA detection) observing system, or augmenting an existing one, to ensure that an optimal set of measurements is included, and the appropriate time frame is planned for.
- Consideration of information such as presented here by the UN Decade of Ocean Science for Sustainable Development (2021–2030) in areas of synthesizing existing research, defining trends, knowledge gaps and priorities for future research, and providing science-based information to inform managers and policy makers, is recommended. Therefore, there is still a tremendous need for long-term support from funding agencies, as well as initiatives and leadership from both within the oceanographic community and beyond.

DATA AVAILABILITY

Publicly available datasets were analyzed in this study. These data can be found here: https://www.socat.info.

AUTHOR CONTRIBUTIONS

DG provided the initial idea for the topic addressed. HW performed the statistical analysis. DT led writing of the manuscript. DT, HW, XH, DG, ZW, LJ, and W-JC contributed to the development, writing, and proofing of this manuscript.

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frontiers in Marine Science

MINI REVIEW
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Advancing Marine Biogeochemical and Ecosystem Reanalyses and Forecasts as Tools for Monitoring and Managing Ecosystem Health

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Ocean ecosystems are subject to a multitude of stressors, including changes in ocean physics and biogeochemistry, and direct anthropogenic influences. Implementation of protective and adaptive measures for ocean ecosystems requires a combination of ocean observations with analysis and prediction tools. These can guide assessments of the current state of ocean ecosystems, elucidate ongoing trends and shifts, and anticipate impacts of climate change and management policies. Analysis and prediction tools are defined here as ocean circulation models that are coupled to biogeochemical or ecological models. The range of potential applications for these systems is broad, ranging from reanalyses for the assessment of past and current states, and short-term and seasonal forecasts, to scenario simulations including climate change projections. The objectives of this article are to illustrate current capabilities with regard to the three types of applications, and to discuss the challenges and opportunities. Representative examples of global and regional systems are described with particular emphasis on those in operational or pre-operational use. With regard to the benefits and challenges, similar considerations apply to biogeochemical and ecological prediction systems as do to physical systems. However, at present there are at least two major differences: (1) biogeochemical observation streams are much sparser than physical streams presenting a significant hinderance, and (2) biogeochemical and ecological models are largely unconstrained because of insufficient observations. Expansion of biogeochemical and ecological observation systems will allow for significant advances in the development and application of analysis and prediction tools for ocean biogeochemistry and ecosystems, with multiple societal benefits.

Keywords: biogeochemical model, ecological model, forecasting, reanalysis, climate projection, scenario

INTRODUCTION

Ocean warming, acidification, deoxygenation and eutrophication are manifesting on global (Bopp et al., 2013; Jickells et al., 2017; Schmidtko et al., 2017) and regional scales (Breitburg et al., 2018; Claret et al., 2018; Irby et al., 2018; Laurent et al., 2018; Fennel and Testa, 2019). These profound changes in ocean physics and biogeochemistry in combination with the ever more efficient harvesting of living marine resources are driving major shifts in marine ecosystems (Cheung et al., 2010; Bianucci et al., 2016; Brennan et al., 2016; Galbraith et al., 2017) with significant societal impacts. Changes in ocean biogeochemistry and ecosystems will also complicate conservation efforts for endangered species but are rarely considered in species recovery planning (e.g., Hartman et al., 2014). Strategies for mitigation, adaptation and protection, ranging from nutrient management in watersheds, fisheries management and Marine Protected Areas, to emission reductions of CO_2 and other greenhouse gases, have to be designed, continuously assessed and revised. This process requires adequate observation of ongoing changes, combined with skillful analysis and prediction tools that provide decision makers and the public with the necessary information to assess the impact of policy decisions.

In this context, the term "analysis and prediction tool" refers to model systems that include realistic representations of ocean circulation coupled with biogeochemical or ecological models. The biogeochemical/ecological model components have a broad range of complexities from simple parameterizations, to fully explicit representations of multiple nutrients and functional groups and serve three major purposes: (1) hindcasts or reanalyses for assessment of past and current states and trends of the system, (2) forecasts ranging from short-term (days to weeks) to seasonal (months) time windows, and (3) scenario simulations including climate change projections and nutrient reduction scenarios. While operational systems are sometimes narrowly defined as only those providing short-term forecasts, we adopt a broader definition here that encompasses the provision of hindcasts and reanalyses, short-term/seasonal forecasts, and scenarios/projections.

Building on the recent review by Gehlen et al. (2015), this article focuses on the current state and future prospect of analysis and prediction tools for ocean biogeochemistry and ecosystems. While the necessity of a tight integration of these tools with observations cannot be overstated, we focus here on the tools themselves. Overviews of the necessary observing system components are given by Roemmich et al. (unpublished) and others in this issue.

CURRENT STATUS

With the goal of illustrating the current status and breadth of ecological/biogeochemical analysis and prediction systems we present a selective overview of global and regional systems. First, we briefly describe two global forecasting systems with biogeochemistry that operate in pre-operational or operational mode to produce short-term forecasts, reanalyses and climate projections (also see Gehlen et al., 2015). We then provide examples of regional analysis and prediction systems (also see **Table 1**). All produce estimates of the biogeochemical ocean state to benefit economic, environmental and public safety needs with users in academia, government, private companies and the general public.

Global Applications

NEMO-HadOCC and NEMO-MEDUSA

The United Kingdom Met Office runs an operational global physical forecasting system referred to as FOAM (Blockley et al., 2014) which is based on the NEMO hydrodynamic model (Madec, 2008), and assimilates satellite and *in situ* data using the 3D-Var NEMOVAR scheme (Waters et al., 2015). FOAM is coupled pre-operationally to two biogeochemical components: HadOCC by Palmer and Totterdell (2001) and MEDUSA by Yool et al. (2013), for reanalyses and Ocean Observing System Simulation Experiments (OSSEs). NEMO-MEDUSA is also used for climate projections as part of the UKESM1 climate model (Kwiatkowski et al., 2014).

FOAM-HadOCC and FOAM-MEDUSA are assimilating satellite chlorophyll using 3D-Var to produce an update of surface $\log_{10}$(chlorophyll), and then calculating multivariate increments for other biogeochemical variables using the balancing scheme of Hemmings et al. (2008). This computationally efficient way to perform multivariate updates has been applied for pre-operational forecasting (Ford et al., 2012) and reanalysis (Ford and Barciela, 2017). A similar approach has also been used to assimilate *in situ* pCO_2 observations into FOAM-HadOCC, by first calculating a surface pCO_2 analysis, and then multivariate balances to DIC and alkalinity (While et al., 2012). Despite the sparse observations, the assimilation produces long-lasting corrections to the model.

FOAM-MEDUSA has the capability to assimilate profiles of chlorophyll, nitrate, oxygen, and pH using 3D-Var (Wood et al., 2018). OSSEs with this coupled system have shown the positive impacts of a BGC-Argo array (Johnson and Claustre, 2016) on model results (Wood et al., 2018).

NEMO-PISCES

Mercator Ocean operationally runs a global physical NEMO model for short-term forecasts and reanalyses. The biogeochemical model PISCES (Aumont et al., 2015) is operated offline in a coarsened 1/4° version of the 1/12° operational NEMO system (Lellouche et al., 2018) for weekly analyses and delivers daily/monthly means and 10-day forecasts.

Operational assimilation of satellite chlorophyll using a SEEK filter (Lellouche et al., 2013) is being implemented with the goal of constraining simulated large-scale structures including chlorophyll amplitudes, extension of oligotrophic gyres, and large-scale blooms. The multivariate scheme is able to provide surface corrections of simulated phytoplankton groups and nutrient concentrations, which are then projected vertically throughout the mixed layer.

NEMO-PISCES is also used for climate projections (Séférian et al., 2012; Bopp et al., 2013) contributing to IPCC assessments. In retrospective forecasts, the multi-year predictability of ocean

TABLE 1 | Examples of analysis and prediction tools for ocean biogeochemistry and ecosystems.

Model acronym, reference	Region[1]	Mode[2]	Product class[3]	Type of DA (if any)	Data used for DA	Data used validation	Link to products
NEMO-PISCES[a]	Global	O, PO, RD	P, R, S	NA	No assimilation of biogeochemical data	Ocean color; *In situ* nutrients, chlorophyll, oxygen, pCO_2, pH	marine.copernicus.eu
NEMO-ERSEM[b]	NWS	O, PO	P, R, S	3D-Var	Ocean color total chlorophyll and PFT chlorophyll; DA for spectral PFT absorption and glider and float data is under development	Ocean color; *In situ* nutrients, chlorophyll, oxygen, fCO_2, pH	marine.copernicus.eu
POLCOMS-ERSEM[c]	NWS	RD	R	EnKF	Ocean color: total chlorophyll; PFT chlorophyll; spectral diffuse light attenuation coefficient	Ocean color; *In situ* nutrients, chlorophyll, oxygen, fCO_2, pH	portal.ecosystem-modelling.pml.ac.uk
ROMS-NEMURO[d]	CCS	PO, RD	P, R	4D-Var	Satellite chlorophyll, physical data	*In situ* chlorophyll, nutrients, oxygen, rates	oceanmodeling.ucsc.edu
eReefs[e]	GBR	PO, RD	R	EnKF	Spectral ocean color	Chlorophyll fluorescence from gliders, *in situ* nutrients	www.ereefs.info
ROMS-ECB[f]	CB	PO, RD	P, R	none	No assimilation of biogeochemical data	Satellite chlorophyll, *in situ* nutrients, oxygen	www.vims.edu/hypoxia; oceansmap.maracoos.org; comt.ioos.us
ROMS-DO[g]	GoMex	PO	P	none	No assimilation of biogeochemical data	*In situ* oxygen	pong.tamu.edu/ tabswebsite
ROMS-Fennel[h]	GoMex	RD	R, S	none	No assimilation of biogeochemical data	Satellite chlorophyll, *in situ* nutrients, oxygen, rates, DIC, alkalinity, pCO_2	comt.ioos.us
OGSTM-BFM[i]	Med	O	R, P	3D-Var	Satellite chlorophyll; BGC-Argo chlorophyll and nitrate (in PO mode); Physical data	*In situ* chlorophyll, nutrients (N and P), oxygen, DIC and Alkalinity	marine.copernicus.eu; medeaf.inogs.it/forecast
MITgcm-BFM[k]	NAdr	PO, RD	P	none	No assimilation of biogeochemical data	*In situ* chlorophyll, nutrients (N and P) and oxygen	medeaf.inogs.it/adriatic
GHER-BAMHBI[j]	Black Sea	O	R, P	SEEK filter	Argo oxygen	Satellite chlorophyll, Argo oxygen, *in situ* nutrients	marine.copernicus.eu

[1]Regional acronyms: NWS, northwest European Shelf Seas; CCS, California Current System; GBR, Great Barrier Reef; CB, Chesapeake Bay; GoMex, Gulf of Mexico; Med, Mediterranean Sea; NAdr, Northern Adriatic Sea; [2]Mode refers to research-driven (RD), pre-operational (PO), operational (O); [3]Product class refers to reanalysis (R), prediction (P), scenarios (S); [a]Aumont et al., 2015; Lellouche et al., 2018; [b]Edwards et al., 2012; O'Dea et al., 2017; Skákala et al., 2018; [c]Ciavatta et al., 2014, 2016, 2018; [d]Song et al., 2016a,b,c; Mattern et al., 2017; [e]Baird et al., 2016, 2018; Jones et al., 2016; [f]Feng et al., 2015; Da et al., 2018; Irby et al., 2018; Irby and Friedrichs, 2019; [g]Hetland and DiMarco, 2008; Yu et al., 2015; [h]Fennel et al., 2011; Laurent et al., 2012; [i]Lazzari et al., 2016; Teruzzi et al., 2018; Cossarini et al., 2019; [j]Grégoire et al., 2008; Capet et al., 2016; [k]Cossarini et al., 2019.

productivity has been explored following decadal prediction protocols (Séférian et al., 2013). The model also has options to represent higher trophic levels of the marine food web allowing investigations of climate change impacts on the whole ecosystem (Lefort et al., 2014).

Regional Applications

Hindcasts and Short-Term Forecasts for the Northwest European Shelf Seas

The Northwest European Shelf Seas (NWS) in the northeast North Atlantic Ocean hosts productive ecosystems of significant interest to several European nations. An operational prediction system for the NWS (Edwards et al., 2012; O'Dea et al., 2017) is maintained by the United Kingdom Met Office. It is based on NEMO (Madec, 2008), and includes a biogeochemical component based on ERSEM (Blackford et al., 2004; Butenschön et al., 2016). The operational forecasting system assimilates physical data using 3D-Var NEMOVAR (King et al., 2018) and provides daily analyses and 6-day forecasts of physical and biogeochemical variables. Assimilation of satellite chlorophyll is currently used for reanalyses and will be implemented for short-term forecasting in the near-future.

Besides total chlorophyll, the system can assimilate a regional ocean-color product for phytoplankton functional types (PFTs, Skákala et al., 2018), which has been shown to improve the plankton community structure and air-sea carbon fluxes in a multi-annual reanalysis (Ciavatta et al., 2018). Developments to allow direct assimilation of ocean color spectral data (Ciavatta et al., 2014) and assimilation of glider and float observations are ongoing.

Reanalysis and Short-Term Forecasts for the Mediterranean Sea

The semi-enclosed Mediterranean Sea is of significant importance to several European, Middle-East and African nations for fisheries, tourism, etc. Decadal reanalyses and short-term predictions for the Mediterranean are produced by an operational NEMO system (Tonani et al., 2014) that is coupled off-line with an assimilative biogeochemical system (Cossarini et al., 2015; Lazzari et al., 2016; Teruzzi et al., 2018). The system uses 3D-Var data for assimilation of physical fields (Dobricic and Pinardi, 2008) and satellite chlorophyll (Teruzzi et al., 2018).

Currently, assimilation of BGC-Argo data is in pre-operational mode (Cossarini et al., 2019) and shows the positive impact of observed chlorophyll and nitrate profiles on simulated vertical phytoplankton distributions throughout the year. A decadal reanalysis with assimilation of physical variables and satellite chlorophyll has shown trends and anomalies in nutrients and air-sea CO_2 fluxes in the Mediterranean (von Schuckmann et al., 2018).

Hindcasts and Short-Term Forecasts for the California Current System

The California Current System (CCS) is a productive upwelling region encompassing waters of the eastern Pacific off the US west coast. A data-assimilative physical-biogeochemical forecast system for this region operates quasi-operationally at the University of California, Santa Cruz (Moore et al., 2013). The system uses ROMS (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008) with a horizontal resolution of 1/10° (Veneziani et al., 2009) and meteorological forcing from COAMPS (Hodur et al., 2002). A 4D-Var method (Moore et al., 2011a,b) is applied to assimilate multiple remotely sensed and *in situ* physical data.

The biogeochemical component is based on NEMURO (Kishi et al., 2007; Fiechter et al., 2014) and constrained using a lognormal form of 4D-Var (Song et al., 2012) to account for the non-Gaussian statistics of biogeochemical observations (see Song et al., 2016a,b,c; Mattern et al., 2017, for more details). Presently only satellite-derived chlorophyll is assimilated, because of its high temporal and spatial coverage.

The system has also been used to produce a 30-year reanalysis (Broquet et al., 2009; Neveu et al., 2016) enabling analyses of regional climate variability (Jacox et al., 2014, 2015, 2016; Crawford et al., 2017) and the identification of habitats for marine fisheries (Schroeder et al., 2014, 2018; Scales et al., 2017) and marine mammals (Becker et al., 2016).

Short-Term Forecasts for Australia's Great Barrier Reef System

The Great Barrier Reef off northeast Australia is a world heritage site but under pressure from agricultural runoff, coral bleaching, crown of thorns starfish outbreaks, ocean warming and acidification, and mechanical damage from tropical cyclones. The eReefs biogeochemical modeling system (Baird et al., 2016) was developed to capture key processes related to water quality including carbonate chemistry (Mongin et al., 2016), bio-optics and bleaching (Baird et al., 2018).

The eReefs system uses a 100-member Ensemble Kalman Filter to assimilate ocean color spectral bands (Jones et al., 2016). The model predicts inherent and apparent optical properties through direct simulation of 17 optically active constituents at 8 spectral bands. This allows for prediction of remote sensing reflectances of the 8 MODIS ocean-color bands and avoids representation errors by directly simulating observed quantities. A reanalysis is available from June 2013 to October 2016. Relative to the assimilation of chlorophyll, forecast errors are reduced by up to 50%, and representation of glider-derived fluorescence and *in situ* observations of nutrients, both withheld from assimilation, is improved by 45 and 20–30%, respectively.

Reanalyses, Short-Term Forecasts and Scenarios for Chesapeake Bay

Chesapeake Bay is a large, productive estuary in the United States that suffers from severe eutrophication and hypoxia. Real-time nowcasts and 2-day forecasts of temperature, salinity and oxygen are produced using the ROMS-based Estuarine, Carbon and Biogeochemistry (ECB) model (Feng et al., 2015; Da et al., 2018; Irby et al., 2018; Irby and Friedrichs, 2019). The forecast system, based in large part on earlier developments by NOAA and the University of Maryland (Brown et al., 2013), uses operationally available forcing from the North American Mesoscale Forecast System and USGS river fluxes. The system of Brown et al. (2013) also predicts the occurrence of several noxious species including jellyfish, harmful algal blooms and water-borne pathogens. While the biogeochemical variables are forecast mechanistically, the species predictions are generated using multivariate empirical habitat suitability models of the target species.

Input from stakeholder meetings has revealed that the ecological forecasts are useful to end-users whose lives and livelihoods depend on Chesapeake Bay, e.g., by guiding recreational and commercial fishermen to productive fishing grounds. The forecasts also inform the Annual Chesapeake Bay Hypoxia Report Card (https://www.vims.edu/research/topics/dead_zones/forecasts/report_card/index.php) which helps managers and the public in assessing water-quality improvements of Chesapeake Bay.

The model has also been used for reanalysis studies quantifying the impact of atmospheric nitrogen deposition (Da et al., 2018) and the uncertainties associated with hypoxia mitigation due to recent nutrient reductions (Irby and Friedrichs, 2019) and future climate change (Irby et al., 2018).

Short-Term Forecasts, Reanalyses and Scenarios of Hypoxia in the Northern Gulf of Mexico

The northern Gulf of Mexico shelf receives large inputs of freshwater and anthropogenically derived nutrients leading to the formation of a large hypoxic zone every summer. A suite of models have been developed to improve understanding of the underlying mechanisms and for operational uses ranging from short-term and seasonal predictions, seasonal and multi-year hindcasts to scenario simulations and climate change projections.

A multi-model intercomparison (Fennel et al., 2016) indicated that a skillful physical model combined with a simple oxygen model (Hetland and DiMarco, 2008; Yu et al., 2015) is sufficient for short-term predictions in this system. A ROMS-based short-term prediction system for dissolved oxygen is run pre-operationally at Texas A&M University[1]. Longer hindcast and scenario simulations use more comprehensive biogeochemical models. The physical-biogeochemical model of Fennel et al. (2011) and Laurent et al. (2012) has been used for multi-year hindcasts to inform fisheries management (Langseth et al., 2014), simulations of nutrient reduction scenarios (Fennel and Laurent, 2018), and future projections of hypoxia and pH conditions (Laurent et al., 2017, 2018). These inform the Hypoxia Taskforce, a multi-agency, multi-state entity charged with devising strategies for reduction of the hypoxic zone and monitoring progress toward this goal (Task Force, 2001).

POTENTIAL BENEFITS, CURRENT STATUS AND CHALLENGES

Ocean biogeochemical and ecological analysis and prediction systems rely on skillful models of ocean physics. Thus, many of the same considerations that apply to operational systems for ocean physics do also apply for biogeochemical and ecological applications but there are important differences.

Potential benefits of biogeochemical/ecological operational systems include (1) the generation of dynamically and internally consistent reanalyses, nowcasts and forecasts through melding of observations with a dynamical model, (2) provision of oceanographic context for observations (from event scale to long-term trends and shifting baselines), (3) estimation of system properties that are not directly observable but can be inferred from dynamical models (e.g., biogeochemical fluxes), and (4) spatial and temporal coverage not attainable by direct observation.

Currently there are only a few operational forecasting systems (i.e., systems maintained by an operational agency with strict commitment to routinely provide forecasts) that assimilate biogeochemical variables and several pre-operational systems (i.e., those run by academics or operational agencies as demonstrations but without commitments for continuous operation). Some will transition to operational mode in the near future (see Section "Current Status" and **Table 1**).

Two main challenges hinder the implementation of biogeochemical and ecological forecasting and analysis systems: data availability, and adequacy of data-assimilation methods. Obviously adequate biogeochemical and ecological observation streams are required in addition to physical ocean observations. Access to biogeochemical observations at meaningful spatial and temporal scales is still limited, especially when required in real-time or near-real time. Currently, the main biogeochemical data stream used in assimilation is satellite ocean color, but this measurement is limited to the surface ocean and provides an imperfect proxy of phytoplankton biomass that, by itself, is insufficient for constraining the multiple biogeochemically active pools in the euphotic zone. Efforts are being made to maximize the benefits of ocean color observations, e.g., by assimilating spectral bands (Baird et al., 2016, 2018; Jones et al., 2016) or satellite-derived PFTs (Xiao and Friedrichs, 2014a,b; Ciavatta et al., 2018; Skákala et al., 2018). The limited availability of observations is especially serious in coastal applications where altimetry and ocean color measurements are compromised by bathymetry and a variety of optical constituents.

Another major difference from physical ocean models is that established assimilation methods (see, e.g., Moore et al., 2019) cannot be applied to biogeochemical and ecological variables in a straightforward manner. Reasons for this include the non-Gaussian characteristics of biogeochemical observations, the strong non-linearity of biogeochemical models and the frequent lack of direct correspondence between convenient observables and model variables. Also, experience has shown that assimilation of physical observations in coupled models often does not improve but degrades the biogeochemical state. Methods for accommodating non-Gaussian distributions are being developed (Song et al., 2012). The strong non-linearity can only be addressed by broadening the suite of observed biogeochemical variables. Although the biogeochemical assimilation schemes described above are multivariate, i.e., assimilation of one variable (e.g., chlorophyll) results in updates to other variables (e.g., nutrient concentrations), the adequacy of these updates hinges on the accuracy of biogeochemical models and is not well tested. Rigorous validation of biogeochemical models and tests of their predictive skill will require increased information content in available data streams. The degradation of biogeochemical fields during physical assimilation appears to arise at least partly when physical and biogeochemical variables are updated independently in violation of property-property relationships and can be substantially reduced by accounting for their correlation (Yu et al., 2018).

In principle, schemes are available for assimilating properties other than ocean color products and data types other than surface observations (e.g., from floats and gliders), but thus far they have mostly been used in OSSE-type twin experiments where synthetic observations are used (Wood et al., 2018; Yu et al., 2018). The

[1] http://pong.tamu.edu/tabswebsite/

true test of these methods has to await better availability of biogeochemical observations.

The prospect of a global BGC-Argo array (Johnson and Claustre, 2016) holds great promise for open ocean applications by expanding the suite of observed properties and extending observations from the surface ocean into its interior (Fujii et al., this issue) but requires careful calibration and verification. BGC-Argo observations will allow for a rigorous validation of biogeochemical models and will provide much better constraints on their dynamics and vertical structure as shown by Cossarini et al. (2019) in the Mediterranean Sea model.

New observations may also elucidate previously unrecognized shortcomings in the dynamical models and prompt modifications/refinements of model structure/formulations. Our best hope for reducing models' structural uncertainty and improving their robustness and predictive skill is model development guided by an expanded observing system in concert with process studies, application of theory, and synthesis of other available information. Data assimilation is best used to correct stochastic variability in state estimates produced by structurally sound models, rather than trying to correct for biases or inappropriate model structures.

CONCLUSION

The potential benefits and scope of applications of biogeochemical/ecological analysis and prediction systems are broad. Presently, the availability of relevant observations is limited, which is a major impediment and explains why biogeochemical/ecological operational systems are still in their infancy compared to physical ocean forecasting. An expansion of ocean observing systems to include more biogeochemical/ecological parameters is crucial for expanded operational services and operational models can help in the design of expanding observing systems.

AUTHOR CONTRIBUTIONS

KF wrote the manuscript with contributions from all authors.

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An Innovative Approach to Design and Evaluate a Regional Coastal Ocean Observing System

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Comprehensive and objective evaluation of all observing assets, tools, and services within an ocean observing system is essential to maximize effectiveness and efficiency; yet, it often eludes programs due to the complexity of such robust evaluation. In order to address this need, the Pacific Islands Ocean Observing System (PacIOOS) transformed an evaluation matrix developed for the energy sector to one suitable for ocean observing. The resulting innovation is a decision analysis methodology that factors in multiple attributes (market, risk, and performance factors) and allows for selective weighting of attributes based on system maturity, external forcing, and consumer demand. This evaluation process is coupled with an annual review of priorities with respect to stakeholder needs and the program's 5-year strategic framework in order to assess the system's components. The results provide information needed to assess the effectiveness, efficiency, and impact of each component within the system, and informs a decision-making process that determines additional investment, refinement, sustainment, or retirement of individual observing assets, services, or component groups. Regularly evaluating, and taking action to improve, modify, or terminate weak system components allows for the continuous improvement of PacIOOS services by ensuring resources are directed to the priorities of the stakeholder community. The methodology described herein is presented as an innovative opportunity for others looking for a systematic approach to evaluate their observing systems to inform program-level decision-making as they develop, refine, and distribute data and information products.

Keywords: ocean observing, program evaluation, prioritization, Pacific Islands, program analysis

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INTRODUCTION

Program evaluation, defined as "systematic investigation to determine the success of a specific program," (Barker, 2003) is an important tool used by organizational managers to inform decision-making with respect to program effectiveness. Coastal and ocean observing programs, in particular regional observing systems, are striving to increase the quality and quantity of the public-facing tools and services they deliver while maximizing value in a relatively flat-growth budget environment. Comprehensive and objective evaluation of all observing assets, tools, and services within an observing system is essential to inform the optimal allocation of resources; yet, the multiple – sometimes conflicting – objectives, preferences, and value tradeoffs inherent within these hybrid scientific-public service programs necessitate a complex evaluation protocol that often eludes observing systems.

Federal disinvestment in Research and Development in the years following the Great Recession have resulted in consistently flat budgets for ocean observing programs nation-wide. Level funding, while more desirable than actual funding cuts, still results in a need to make tough decisions with regard to resource allocation. In a typical year, program costs increase for salaries, wages, and fringe benefits, and buying power decreases due to inflation. In other years, negotiated indirect cost rates increase, resulting in what is in effect, a direct cut to the program. While horizontal cuts can help alleviate the impacts for some time, there is a tipping point in budgets when system services cannot operate effectively; requiring the consideration of vertical (whole service) cuts. In 2012, Pacific Islands Ocean Observing System (PacIOOS), the first federally certified regional component of the U.S. Integrated Ocean Observing System (IOOS®; Ostrander and Lautenbacher, 2015) started to reach this tipping point, and vertical cuts needed to be considered. The PacIOOS management team and Governing Council agreed that an objective method to evaluate the various components was necessary. In order to better assess program effectiveness and inform the allocation of annual and future investment, PacIOOS transformed an evaluation matrix developed for the energy sector (Waganer, 1998; Waganer and the ARIES Team, 2000) to one suitable for a coastal ocean observing system.

The resulting innovation is a decision analysis methodology that factors in multiple attributes (e.g., market, risk, economic, and performance factors) and allows for selective weighting of attributes based on system maturity, external forcing, and consumer demand. In 2013, PacIOOS began utilizing this evaluation process coupled with an annual review of stakeholder priorities and the program's 5-year strategic framework to assess the system's components. The results provide information to analyze the effectiveness, efficiency, and impact of each component within the system and inform a decision-making process that determines additional investment, refinement, sustainment, or retirement of individual observing assets, services, or component groups.

Regularly evaluating and taking action to improve, modify, or terminate weak system components allows for the continuous improvement of PacIOOS services by availing limited resources to address the evolving priorities of stakeholders. The methodology described herein is presented as an innovative opportunity for others looking for a systematic approach to evaluate their observing systems to inform program-level decision-making as they develop, refine, and distribute timely, accurate, and reliable data and information products.

INNOVATING AN EFFECTIVE DECISION ANALYSIS METHODOLOGY

Evaluation Attributes

In order to ensure a balanced appraisal of diverse PacIOOS services (e.g., high-frequency radars, wave buoys, data systems, outreach programs, etc.), the program requires a decision analysis methodology that factors in multiple attributes and allows for selective weighting of attributes based on enterprise maturity and external forcing. Review of modern evaluation systems in corporate and non-profit systems (Conley, 1987; Keeney and Raiffa, 1993; Waganer, 1998; Wholey et al., 2010) yields numerous potential attributes an enterprise can consider when evaluating service effectiveness. Due to the perceived importance of the decision makers, the identification of attributes for evaluating, and the weighting of those attributes may be somewhat subjective; however, chosen attributes are valuable not only for a consistent annual review but also for the analysis of trends over multiple evaluation cycles.

Market, risk, and economic factors were considered in the selection of evaluation attributes for PacIOOS. Market factors help determine the potential for each service to fulfill a needed role among stakeholders, while economic considerations allow for the review of competing services, resource commitment, and future cost considerations. Risk is assessed in the return on capital, maturity of the service, annual resource requirements, and independent performance of the assessed service.

A sample of the attributes gleaned from systems examined (Conley, 1987; Keeney and Raiffa, 1993; Waganer, 1998; Wholey et al., 2010) but not selected by PacIOOS for evaluation purposes include the following: liquidity; time to market; leverage (debt); profit; policy landscape; public perception; revenue diversity; prestige; competitiveness; return on investment; depletion of valued resource; supply chain dependence; environmental impact. As evidenced by this list, even in commercial models, revenue and other economic factors are not the only attributes of interest when evaluating success of a company or a system. The institutional vision, mission, and values, or guiding principles, of an organization provide the foundation by which that organization should be measured and evaluated. PacIOOS' core vision, mission, and guiding principles are the framework that informed which attributes to employ for this evaluation process. The attributes selected by PacIOOS for use in the evaluation of each program service are described below.

Need

Has the service been identified by stakeholders as critical and desired? If so, does a large and diverse (geography, organization type, interest sector) cohort of the stakeholder community desire the service?

Uniqueness

Do any other providers deliver a similar or identical service to stakeholders in the PacIOOS region? If so, does the similar service provide a greater, lesser, or same level of utility?

Potential

Is this service, as intended, conceived, and fully applied likely to significantly improve the health, safety, economy, or environment of stakeholders in the region?

Financial Capital

Is the current funding of service operation, per year to maintain operations (not including recapitalization), sufficient for stable operation of the service?

Human Capital

Does the service require a significant commitment of human capital above those individuals required for direct operations and maintenance (i.e., does it need individuals from other enterprise components like data management, outreach, executive leadership) to continue operation?

Integration

Is the service part of a regional, national, or global network of complementary services (e.g., sole regional node within the United States national high frequency radar network)? If so, is it a critical component within the larger network? Also, has the service been integrated into the operations of local stakeholders (e.g., wave buoy data used to inform a National Weather Service surf forecast) and/or into other program operations (e.g., high frequency radar data ingested into regional ocean model)?

Technical Maturity

Does the service need improvement to function as intended? Is the technology still under development?

Saturation

Does the entire identified stakeholder base utilize the service? Can more customers be identified to utilize the service?

Required Service

Is the service required through an agreement maintained with a partner (i.e., service contract), a core part of the national IOOS® program, and/or the recipient of directed federal resources (e.g., supplemental appropriation to purchase specific equipment)?

Incremental Cost

Does the service need to be repaired, recapitalized, or is further investment needed?

Performance

Is the service reliable? How often is the service unavailable per year?

Scoring

The program's executive leadership and board assigned attribute weights to each attribute (ranging 1–3), based on their perception of the importance of each attribute to the total assessment of the program. Specific attribute values for each service are scored on a scale ranging from 1 (lowest score) to 5 (highest score), based on an established rubric for each attribute. The assignment of clear attribute values, and consistent use of them, is an important step toward removing subjectivity from the annual evaluation process and helping ensure a higher degree of consistency between annual cycles, evaluators, and funding scenarios.

For example, the first attribute in the evaluation is Need. The evaluators assign a score under Need for each program service evaluated based on the following rubric:

Need

Has the service been identified by stakeholders as critical and desired? Does a large and diverse (geography, organization type, interest sector) cohort of the stakeholder community desire the service?

(1) No desire for service has been identified within stakeholder community.
(2) Service is viewed as "nice to have" by some but not considered to be critical by any.
(3) Service is desired by a diverse set of stakeholders, and has the potential to become critical to their operations.
(4) Service has been identified as a critical tool for a small set of the stakeholder community.
(5) A large and diverse stakeholder base identifies the service as critical.

For PacIOOS, the wave buoy program typically scores a 5 under Need, as there are numerous and diverse stakeholders that identify the information these assets provide across our region as critical. Stakeholders include, but are not limited to, the National Weather Service, the United States Coast Guard, the United States Navy, natural resource managers, university researchers, ocean engineers, commercial fishermen, and recreational ocean users. Through stakeholder engagement, surveys, and other feedback received, it is clear that the wave buoys aid all of these stakeholders by providing real-time information that is deemed critical for their decision-making needs.

After the attributes and weights are established, an additive utility theory methodology is used to quantitatively evaluate each service. Additive, as opposed to a multiplicative utility function, was chosen for this process as a score of zero under any attribute would return a total score of zero under a multiplicative function. Multiplicative scoring might be appropriate if all aspects of the enterprise were fully developed; however, enterprise maturity and continual evolution of PacIOOS services necessitates careful and objective consideration of services that are under development. Using an additive utility function will partially penalize developing services, but not eliminate them from further consideration (Waganer and the ARIES Team, 2000).

The score for each service within the program is determined by summing, across all attributes, the product of the weight and value for each attribute. The weighted score calculation, illustrated below as an equation, has the potential to produce scores ranging from 0 to 210. **Table 1** provides a complete example calculation of a weighted score for a PacIOOS service.

$$Score \sum_{n=1}^{14} Weight_n \ Value_n$$

As noted in the previous section, while the assigned weights might seem arbitrary, both the weights and the rubric remain consistent across time. This allows for the opportunity to examine each individual service as well as the overall system performance from year to year and over time.

TABLE 1 | Example calculation of a weighted score for a PacIOOS service.

Attributes	Need	Uniqueness	Potential	Financial capital	Human capital	Integration	Technical maturity	Saturation	Required service	Incremental cost	Performance	Weighted sum
Weight (1–3)	2	3	2	1	2	2	2	3	1	2	1	
Scores (1–5) example service	2	4	3	1	4	5	4	4	3	4	3	
Value (weight*score)	4	12	6	1	8	10	8	12	3	8	3	75

Decision-Making

The resulting assignment of annual scores for each PacIOOS service is a major component of an established review process to inform program-level decision-making, but it is not the *only* component of the process. Stakeholder needs and priorities garnered during ongoing engagement, realities of current capacities of the program and across the region, and the program's 5-year strategic framework are also essential pieces of this matrix. PacIOOS' Governing Council, other signatory partners, and PacIOOS staff and researchers all inform the goals and objectives within the 5-year strategic framework. In this manner, they also help inform the annual decision-making of the program.

If a tool or service is found to be less successful during evaluation, this is the opportunity for an in-depth qualitative analysis to examine the reasoning behind the result. PacIOOS management explores the potential for the low-scoring service to improve with the allocation of additional resources (e.g., funding, staff time, outreach, etc.), or if there are opportunities to modify the service in some manner to bring it to the next level. If so, and internal resources are available to make such improvements or modifications, then the necessary adjustments to effort and funding are implemented as part of the program. If internal resources are not available to enhance or modify the component as needed, management examines opportunities for external resources to support the desired changes. Where feasible, the program helps to secure such external resources to facilitate the improvement of the service for the enhanced benefit of stakeholders. If external resources are not available, the program may examine if a partner organization has the capacity to improve upon it, or operate the service. If there are no such options, the resulting decision may be to discontinue the service. In other cases, when the program cannot identify opportunities to modify a low-scoring service in order to improve its performance, this is also a signal to the program to seriously consider discontinuing the service.

This inquiry process helps to ensure the continuation of successful services, the refinement or reinvestment in developing services, and the termination or transfer of underperforming services. Indeed, PacIOOS has employed this methodology to inform difficult decisions such as vertical cuts, refinement of service aim, and bolstering support for other components. As illustrated in **Figure 1**, this decision-making process ensures the outcomes of the evaluation scoring are both incorporated into and informed by ongoing stakeholder engagement, long-term strategic goals and objectives, and the regional context of the program. Inter-annual consideration of service scores, by attribute, allows PacIOOS to regularly evaluate program success toward achieving maximum service value.

Utilizing Evaluation Results to Improve: PacIOOS Examples

In 2014, following 2 years of annual evaluation, PacIOOS implemented its first vertical cut. There were two services that year that scored much lower than the other services evaluated. At this point, the qualitative review (see **Figure 1**) was

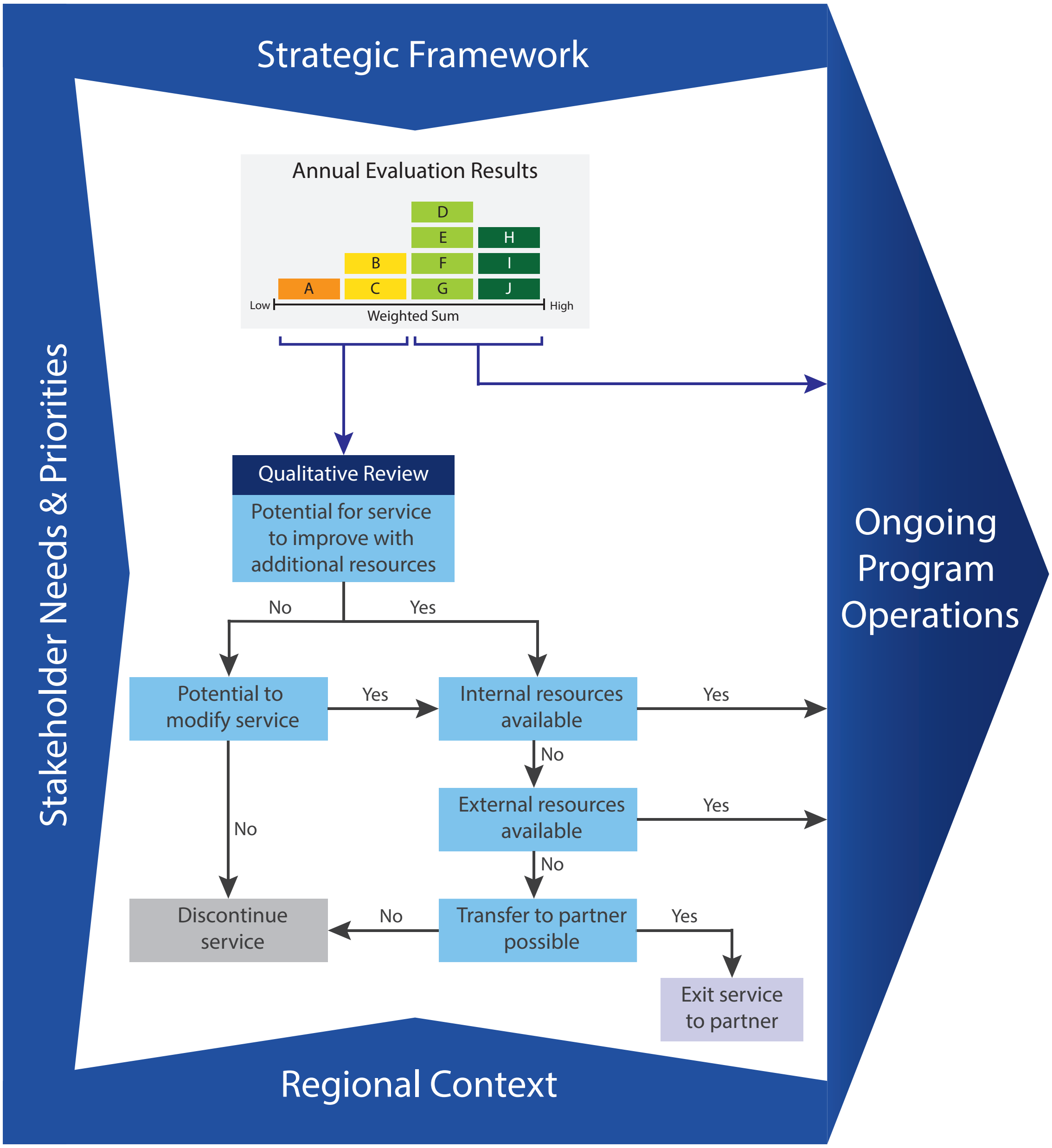

FIGURE 1 | Decision-making process diagram for consideration of annual service evaluation outcomes.

employed. For service A, it was clear that additional resources would not improve the service performance. Rather, it was a situation in which assets inherited from a partner served a very localized (almost individual researcher) need, at a high relative cost, and were poorly aligned with both the strategic goals of the program and the defined needs of the broad stakeholder community. Relevant federal and local partners viewed the assets as "nice to have" but not critical and were not interested in providing additional support, leading PacIOOS to discontinue funding service A.

For the other low scoring service, labeled here as service B, in depth discussions with staff, researchers, leadership, and regional liaisons highlighted some significant aspects of the issue. While some of the assets within service B were of value to stakeholders, a few were underutilized and performing so poorly that they were bringing the assessment of the whole service down. However, the assets within service B addressed a long-term strategic goal of the program: increasing observational coverage across the region geographically. In addition, it had the potential to help address a strategic objective to foster the capabilities for ocean observing in the Insular Pacific and to address identified needs of stakeholders. Similar to service A, it did not seem that additional resources alone would improve the service. The team then asked whether the service could be modified in some way to improve it. After examining numerous options within the larger context of the program's guiding principles (i.e., culturally rooted, stakeholder-driven, collaborative, science-based, and accessible) and the long-term strategic goals and objectives, leadership implemented a pilot project by removing the instruments from the two worst performing sites and making them available to shorter-term (6 months to 2 years) projects of program partners, along with training of how to maintain and operate the instrument and data management support. This pilot project has become successful in terms of forging new partnerships, helping address stakeholder needs, increasing capacity in the region, and communicating the benefits of ocean observing in general, and PacIOOS specifically – aligning well with the values and goals of the program.

Four years later, this small instrument loaner program has aided five different partners serving stakeholder needs across locations in Hawaiʻi, The Federated States of Micronesia, Palmyra Atoll, and Palau. The low evaluation score in the case of service B objectively shed light on a weakness within the program and provided an opportunity to examine its potential for improvement. In the end, the team was able to improve it through modification, thereby lifting up the entire service.

These examples highlight the importance of evaluation within a clearly defined program mission – and strategic plan that guides action toward specific program goals. The evaluation is set up with the assumption that an organization's structure is already built upon a foundation of a strong vision, mission, guiding principles, and strategic goals. However, these specific values, guiding principles, and goals will certainly vary among observing systems to some degree. A low evaluation score does not automatically mean a service should be discontinued, but it does signal the need for a deeper discussion about the goals of the service, the goals and values of the program, and options for making both of them better.

SUMMARY

While optimal program effectiveness is a rather subjective goal, there are tools for evaluation and decision-making to help managers and leaders arrive at relatively objective conclusions. This paper describes an innovative approach that PacIOOS' leadership and management refined and adopted in order to account for market, risk, economic, and performance factors as they collaborate to sustain and enhance a regional coastal and ocean observing system that addresses stakeholder needs.

Once the evaluation tool is established, personnel that are intimately familiar with all aspects of the program and its various tools and services utilize it to provide a more objective base to inform their decision-making. Paired with other programmatic and stakeholder knowledge, evaluation results can be used to ensure a program remains relevant, forward looking, and effective.

Ocean observing systems across the globe, including at all scales from deep ocean to coastal waters, share a common vision to help improve the lives and livelihoods of people and communities. We encourage those in the coastal and ocean observing world to continue to think about how they can have a greater impact on the varied stakeholders in their respective communities, regions, states, and nations. Indeed, in ocean observing, stakeholder needs, observing and data management technologies, program capacities, and more continuously evolve. In order to remain relevant to stakeholders and partners and be as effective as possible, observing systems need to evaluate how they allocate limited resources. As such, this process is helpful for developing as well as more mature programs. It is never too late to evaluate and reassess a program's success, however, it may be defined.

Pacific Islands Ocean Observing System has benefited from this methodology over the past 6 years, and we hope it may inspire or help others that are looking for a way to measure the effectiveness (however, they define it) of their various components or efforts and utilize those outputs to inform programmatic decision-making. Although the specific attributes chosen might not be the same ones that another ocean observing system prefers to use, the framework of how to refine and employ such a methodology may prove beneficial.

This methodology also highlights the value of looking to other industries or organizational frameworks for potentially innovative ideas that may translate to coastal and ocean observing systems. While it may not be optimal to always take a corporate mentality when operating an observing system, there are lessons to be learned and tools that can be adjusted to accommodate for other needs and circumstances. Transforming tools made for others to fit the needs of ocean observing can save resources, improve efficiency, and ultimately, increase the benefits to society.

AUTHOR CONTRIBUTIONS

CO conceived and designed the evaluation process. CO, MI, and FL refined the process. MI organized the development of the manuscript and, with CO, contributed the language that served as the foundation of the manuscript. FL designed the figures and tables. All authors contributed to manuscript revision and have read and approved the submitted version.

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REVIEW
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The Challenge of Sustaining Ocean Observations

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Sustained ocean observations benefit many users and societal goals but could benefit many more. Such information is critical for using ocean resources responsibly and sustainably as the ocean becomes increasingly important to society. The contributions of many nations cooperating to develop the Global Ocean Observing System has resulted in a strong base of global and regional ocean observing networks. However, enhancement of the existing observation system has been constrained by flat funding and limited cooperation among present and potential users. At the same time, a variety of actors are seeking new deployments in remote and newly ice-free regions and new observing capabilities, including biological and biogeochemical sensors. Can these new needs be met? In this paper, a vision for how to sustain ocean observing in the future is presented. A key evolution will be to grow the pool of users, engaging end users across society. Users with shared values need to be brought together with commitment to sustainable use of the ocean in the broadest sense. Present planning for sustained observations builds on the development of the Global Ocean Observing System which has primarily targeted increased scientific understanding of ocean processes and of the ocean's role in climate. We must build on that foundation to develop an Ocean Partnership for Sustained Observing that will incorporate the growing needs of a broad constituency of users beyond climate and make the case for new resources. To be most effective this new Partnership should incorporate the principles of a collective impact organization, enabling closer engagement with the private sector, philanthropies, governments, NGOs, and other groups. Steps toward achieving this new Partnership are outlined in this paper, with the intent of establishing it early in the UN Decade of Ocean Science.

Keywords: sustained, ocean observation, partnership, shared value, society

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INTRODUCTION: THE VISION FOR SUSTAINED OCEAN OBSERVATIONS

Today, nations, the private sector, and many other sectors of society are looking to the ocean for more resources and expanded uses. The oceanographic community has recognized that understanding and adapting to climate change—with ocean impacts ranging from sea level rise to poleward shifts of valuable fisheries—will require additional monitoring of ecosystems and the biogeochemical and physical properties of the ocean. However, the drivers for sustained ocean

FIGURE 1 | The 17 sustainable development goals identified by the United Nations to build toward a better and more sustainable future and address the global challenges faced by society. (UN, 2018a)[1].

observations are much broader and the support developed to date for ocean climate observations is insufficient to support the sustained ocean observing system that is needed. Our focus here is to recognize these diverse needs and stimulate discussion of how to assemble these future users and motivate the higher level of support required.

The additional requirements for ocean observations come from activities that range from fishing to mining and from generating clean energy to finding new genetic resources. Experience has led to general agreement among the ocean constituency that following the UN Sustainable Development Goals will be essential for the future development of ocean resources. Of the 17 UN goals, just Goal 14 is focused on the oceans; but the goals for food, energy, infrastructure, cities and protection are also linked with the marine environment (**Figure 1**). At the UN Ocean Conference in June 2017, governments, the private sector, NGOs and most of the ocean community committed to working within such a framework. Achieving and maintaining sustainability requires a comprehensive base of information fed by long-term observations.

The specific targets in the ocean-focused Goal 14 (UN, 2018b)[2] are to:

1. Stop pollution
2. Manage and restore ecosystems
3. Minimize acidification
4. Stop illegal fishing
5. Conserve 10% of ocean areas
6. Stop fishing subsidies
7. Help small island states through sustainable management
8. Increase scientific knowledge.

Of these 8 targets, at least 6 would benefit directly from long-term observations: stop pollution, manage and restore ecosystems, minimize ocean acidification, stop illegal fishing, conserve 10% of ocean areas, and increase scientific knowledge. To be useful, more processes at more locations need to be monitored. New technology will be enabling, ranging from autonomous vehicles and artificial intelligence to new kinds of measuring instruments. But the main point is that if society is to operate in a sustainable mode, much more information from the ocean is needed.

The complex social, industrial, military, economic, and environmental landscape within which a wide range of communities interact to achieve these Sustainable Development Goals presents a challenge both for maintaining and expanding ocean observations. Within this landscape, though, there is immense opportunity for working together to achieve common goals of sustained ocean observations for the benefit of society. Such an effort would ensure coordination, communication, and shared agendas across multiple communities, and could result in a collective impact that exceeds the sum of the individual efforts at monitoring our oceans for the benefit of society. In this white paper, we outline a strategy for a new form of "Collective Impact Organization" (Kania and Kramer, 2011) that would inform a path forward for the support of sustained ocean observations.

In section The Social and Environmental Landscape we set the context of need for and benefit from sustained ocean observations by exploring the social and environmental landscape. In section The Foundation for Going Forward: The Present Approach to Sustaining Ocean Observations we summarize the present approach to sustaining ocean observations, pointing to the present international context for global ocean observations. Section The Future: An Ocean Partnership for Sustained Observations as a Collective Impact Organization presents our recommendation—a future ocean partnership for sustained observing, and sections Next Steps and Making OceanObs'19 a Stepping-Off Milestone outline the next steps that would lead to development of this partnership.

THE SOCIAL AND ENVIRONMENTAL LANDSCAPE

The 2017 consensus report by the National Academies of Sciences, Engineering, and Medicine (NASEM) on *Sustaining Ocean Observations to Understand Future Changes in the Earth's Climate* (National Academies of Sciences, Engineering, and Medicine (NASEM), 2017) (hereafter referred to as the NASEM 2017 report), recommended development of a clear, national-level plan for long-term ocean observing that is consistent with and complementary to international plans. Although ocean observing is a global enterprise, the U.S. has been a leader in both the development and implementation of observing systems, serving both domestic and international interests. Hence, development of a national-level plan in the U.S. would boost support for ocean observing globally. The report also supported the creation of an organization to promote partnerships across sectors to be called the Ocean Climate

[1]https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[2]https://www.un.org/sustainabledevelopment/oceans/

Partnership. The motivation for the NASEM 2017 report came from the recognition that a full understanding of the ocean's role in climate requires long time series of ocean variables. To realize the full value of these time series, there must be continuity, sufficient sampling frequency to avoid aliasing, and records with the quality and spatial resolution required to detect the signals of interest (Baker et al., 2007). For understanding climate processes, sustaining the measurements for many decades will be required; presenting a formidable, intergenerational challenge (Wunsch et al., 2013). Although the NASEM 2017 report is a substantive summary of these needs and challenges for climate observations, additional discussions during the development of the present white paper brought us to the conclusion that a broader global ocean partnership would better represent the spectrum of interests and values of ocean observing. Therefore, in this section, we focus on needs for sustained ocean observing in addition to those for climate.

Improving Weather Forecasting on Sub-seasonal to Seasonal Time Scales

Observations of sea surface temperature (SST) have long been utilized in routine short-term forecasting to initialize numerical weather prediction models. But now there is evidence that inclusion of additional ocean information will improve sub-seasonal to seasonal forecasts. Forecasts on this extended timescale will support advance planning in applications such as anticipation of droughts to inform farmers and water resource managers as well as to help reduce weather-related economic losses and increase protection of life and property (National Academies of Sciences, Engineering, and Medicine (NASEM), 2016). Continuing these improvements in forecasting skill will depend in part on additional observing information, such as sea surface salinity (SSS) combined with new technological approaches like using machine learning/artificial intelligence for enhanced data analysis.

The influence of SST on the patterns of atmospheric circulation have long been recognized and utilized for statistically—based seasonal forecasts (Namias, 1959, 1978; Palmer and Zhaobo, 1985; Kirono et al., 2010). Even longer timescales of climate variations (decades) have been fruitfully hind-cast using SSTs (Czaja and Frankignoul, 1999; Enfield et al., 2001; Ummenhofer et al., 2008, 2009). At seasonal and decadal time scales, the influence of the ocean heat reservoir has predictive value for atmospheric conditions. Similarly, numerical models can be run-out to about 1 week lead before the sensitivity to initial conditions degrades accuracy (the chaos effect). However, less is known about the sub-seasonal gap between 1 week and 3 months, where improving such forecasts is an active area of research (National Academies of Sciences, Engineering, and Medicine (NASEM), 2016; Zhu et al., 2017).

Artificial Intelligence techniques are now being applied to ocean data to improve seasonal and sub-seasonal predictions (Abbot and Marohasy, 2012; Li et al., 2018). Moreover, recent analyses indicate that SSS information adds surprising skill to seasonal predictions of rainfall on land (Li et al., 2016a,b). Teleconnections between SSS in certain oceanic regions and terrestrial rainfall one season later are likely due to the role of SSS as an indicator of the net moisture export from the ocean. Liu et al. (2018) find that SSS is superior to SST and other traditional climate indices for autumn lead predictions of winter precipitation in the US Southwest. This is just one example of advances in sub-seasonal to seasonal forecasting through the combined use of Artificial Intelligence tools and Bayesian statistical techniques applied to an expanding suite of ocean state variables. These advances are expected to have tremendous societal benefit at a time of intensifying storms, severe floods, and prolonged droughts.

The Blue Economy: Food and Mineral Resource Extraction

Can There be a Sustainable Blue Economy?

The World Bank defines the Blue Economy as "the sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health." A study by the OECD (OECD, 2016) estimated that the blue economy will double its fraction of global value added, outperforming the rest of the economy. The potential for growth throughout the blue economy will depend on the overriding principle that sustainability is at the heart of maintaining ocean resources and making them available to future generations. Society has learned that unless sustainability is built into resource management from the beginning, the environment suffers and living resources will decline (Roberts and Ali, 2016). Ocean users will be challenged to apply this to the development of new industries, such as deep-sea mining. In the Arctic, there will be an opportunity to apply these principles in a relatively pristine ocean as reduced summer sea ice opens this area for ice-free navigation for the first time in all of human history.

Fisheries

On a global basis, wild fisheries catch continued to rise through most of the Twentieth century as fisheries expanded into new regions and exploited ever more fish stocks. Then in the early 1990s, despite increased effort and fishing subsidies, wild fisheries catch began to level off at about 90 million tons/year. Since then, the major increases have come from farmed fish and other aquaculture (FAO, 2018)[3] (**Figure 2**).

As world population grows, nations are looking to find more food from the sea. But as we have seen from wild fisheries, we may be at the limit. Can the steady level of wild fish catch and growth of aquaculture continue? A fundamental part of the answer to that question is knowledge of the state and long-term changes in the marine environment. What natural fluctuations can we expect? How will climate change influence the habitat, locale, and productivity of fish stocks? Our knowledge of the changing environment and of global fish resources is still imperfect; the dynamics of many fish population remain uncharacterized. An effort to catalog our knowledge of marine biodiversity, the Census of Marine Life was first undertaken in 2000–2010 (Census of Marine Life, 2018)[4], underscoring how

[3]http://www.fao.org/state-of-fisheries-aquaculture/en/
[4]http://www.coml.org/about-census/

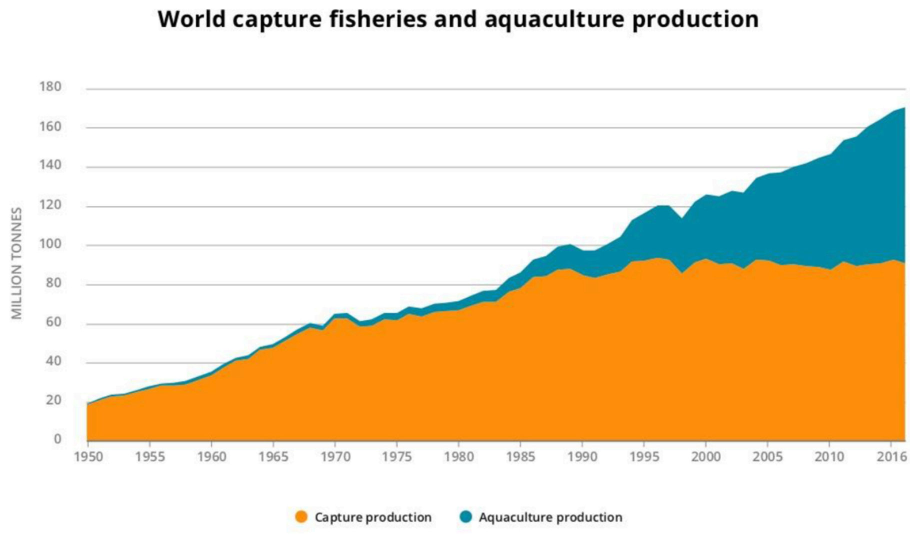

FIGURE 2 | Time history of fish caught and produced by aquaculture. From FAO, 2018.

much remains to be learned about the diversity and functional properties of ocean ecosystems.

New ways of monitoring marine ecosystems and marine biodiversity promise to revolutionize our ability to track invasive species, develop early detection of harmful algal blooms, monitor endangered species, assess the health of fish stocks, and explore the world of marine microbes. High throughput DNA sequencing has made it feasible and economical to analyze minute quantities of DNA in environmental samples. This has fostered the development of environmental DNA (eDNA) as a new "sensor" for monitoring marine biota. Because larger marine organisms shed DNA into the environment, eDNA allows detection of a species in a discrete (e.g., 1L) water sample without the requirement to capture or visually detect their presence (Hansen et al., 2018) and has proved to be an efficient way to monitor habitats (Yamamoto et al., 2017). Although eDNA provides exquisitely sensitive information about the presence and location of marine species, applications for assessing abundance, for example for fish stock assessment, are still unproven.

Passive acoustic monitoring—the detection of sounds emitted by marine organisms—provides another non-invasive approach for monitoring species and ecosystems (Van Parijs et al., 2009; Freeman and Freeman, 2016). Because acoustic signals propagate long distances in water, hydrophones can be deployed as a sensor to efficiently assess the distribution of animals that produce species-specific sounds, such as krill (Watkins and Brierley, 2002).

Deep-Sea Mining

In the latter part of the Twentieth century, the Law of the Sea Convention was put in place originally driven by the expected need for equitable allocation and recovery of deep-sea mineral resources. But the engineering challenges of profitable large-scale mining have limited investments. Now interest is growing: as of 2018, there are 29 approved contracts for exploration under the International Seabed Authority, and mining of critical materials may begin within the year (Pew Trusts, 2017)[5] But, since data from the deep-sea environment are so sparse, any mining that takes place will be done mostly in ignorance of the harm that might be done. Ideally there would be characterization of the seabed biota and ongoing observations of the marine environment around a potential mining site—both before the mining takes place, during the mining, and then afterwards. Otherwise, deep-water species and ecosystems may be damaged without awareness or appreciation of what has been lost. Extensive experience with land-based mining has shown the destructiveness of mineral extraction in the absence of effective environmental standards.

An Ice-Free Arctic Ocean

Sometime in the second half of the Twenty-First century, it is highly likely that climate change will cause the Arctic Ocean to become ice-free in the summer, opening it up to shipping, fishing, and drilling for oil and gas (Mahlstein and Knutti, 2012). Data collected over decades, especially to understand the ongoing changes as the Arctic warms, will be necessary to ensure that these new activities will in fact enable the sustainable use of the new resources, both mineral and living, that could be exploited.

Blue Economy: Non-extractive Resources

Genetic Resources/Biosynthesis/Medicines From the Sea

Most drugs have been developed from bioactive compounds found in plants, fungi, or microbes on land, but the discovery of new compounds has dwindled. The sea has been a source of anti-cancer compounds and antibiotics, and the search has become more urgent as the spread of multi-drug resistance

[5]http://www.pewtrusts.org/en/research-and-analysis/fact-sheets/2017/02/deep-sea-mining-the-basics

has crippled the efficacy of many current antibiotics. For example, corals and sponges have chemicals that can fight some of the most virulent bacteria (NOAA Medicines, 2018). The European Union is carrying out deep-sea sampling, genome scanning, chemical informatics, and data-mining to find more useful medicines (World Economic Forum, 2016)[6] Concomitant long-term observations of the relevant biological, chemical, and physical ocean environment are necessary to ensure that sources of potential new pharmaceuticals are not lost and are harvested sustainably.

Sources of Renewable Energy

The coastal ocean is home to large numbers of wind farms in Europe and offshore wind facilities are expanding in the U.S. and elsewhere. The long-term effects on marine biota of these relatively new installations are unknown. Experience from decommissioned oil rigs has indicated that the introduction of new structures increases substrate for sessile organisms and many fish species are attracted to structures, although the effect on fish abundance is largely unknown (Macreadie et al., 2011). But what is the long-term impact?

Of particular interest for providing power for coastal sensors and autonomous vehicles, the use of energy from tides and waves is expected to grow with the increasing demand for green energy (Yang and Copping, 2017). The same may be true of ocean thermal energy generation, based on the temperature difference between shallow and deep water. These technologies are feasible today, but only in a few places. However, demand for renewable energy sources could lead to an increasing number of structures for offshore wind and hydrokinetic energy capture. Long term observations will help in the selection of sites for installation and will provide environmental parameters for design specification and ecological monitoring. Planning is needed for effective placement of offshore energy activities, and knowledge is critical for the planning.

A longer-term effort is aimed at transforming microscopic algae into cells that take in CO_2 and become a source of biomass fuel. If feasible, this algae-based biofuel could provide many benefits. Although these operations are still in the research phase (Khan et al., 2018), any sustainable and low impact use of these techniques in open systems on a large scale will require long-term biological, physical, and chemical observations.

Reducing CO_2

Using iron fertilization to promote algal growth has been proposed as a strategy for sequestering additional atmospheric CO_2 (National Research Council (NRC), 2015). However, the fraction of CO_2 that remains sequestered in organic material (rather than being consumed and respired) has yet to be determined and there are serious concerns about the possible effects on ocean ecosystems. More needs to be known about carbon cycle in the ocean to estimate the potential for sequestration and assess the long-term impacts of large-scale fertilization. An alternative strategy is the conservation and restoration of coastal vegetation, often referred to as coastal blue carbon (NOAA, 2018a). This approach is based on the sequestration of organic carbon in sediments from marshes, mangroves, and seagrass beds. Evaluation of the long-term growth and stability of these coastal carbon stores will require additional monitoring.

Fresh Water From the Sea

The UN has warned that by 2050 the world is in danger of not having enough fresh water for the people who need it (UN Dispatch, 2017).[7] Despite the costs, coastal states are ramping up their desalination efforts; for example, Israel, Jordan, and Palestine just agreed to a plan to bring in and desalinate water from the Red Sea. Can the ocean solve the global freshwater crisis? Although costs have deterred major deployment of desalination plants in coastal states, the increasing water shortages may lead to more construction. What will be the impact on the coastal ocean from the deposition of concentrated brines? Monitoring should start now to establish a baseline.

Fleets of Autonomous Vehicles

Traditional users are rapidly adopting robotic technology, which will greatly expand the volume of the ocean which can be monitored and measured. Newly built internet infrastructure will make it easy to transfer data around the world. Shipping companies and navies are rapidly developing large autonomous ships, heavily dependent on artificial intelligence, to replace container ships and some naval operations. Fleets of robots could be useful for fisheries enforcement. These large vehicles will require large amounts of data to feed new artificial intelligence systems. Stone and Degnarain (2017) have suggested digital avatars connected to data sources and the Internet of Things that would run simulations based on large amounts of data—an idea similar to that of Henry Stommel's unmanned underwater gliders called Slocum Drifters (see e.g., Stommel, 1989). In any case, most of the data required will come from long-term ocean observations.

Coastal Development

Coastal development for housing, recreation, tourism, and shipping has an impact on the coastal ocean through destruction of habitat, sedimentation, and polluted runoff and air. Sustainable development will require monitoring and reduction of impacts on ocean and coastal ecosystems.

THE FOUNDATION FOR GOING FORWARD: THE PRESENT APPROACH TO SUSTAINING OCEAN OBSERVATIONS

Having presented examples of needs for sustained ocean observing in addition to climate, it is important to consider the development to date of sustained ocean observing, to acknowledge the progress that has been made, and then to highlight the challenges that the present approach has faced.

[6]www.weforum.org/agenda/2016/09/12-cutting-edge-technologies-that-could-save-our-oceans/

[7]https://www.undispatch.com/bad-news-world-will-begin-running-water-2050-good-news-not-2050-yet/.

Ocean observing capabilities matured greatly in the latter half of the Twentieth century and early Twenty-First century (**Figure 3**). The previous OceanObs'99 and OceanObs'09 conferences were milestones; these meetings and the intergovernmental efforts to establish a global ocean observing system, or GOOS, laid the foundation for our present sustained ocean observing efforts. **Figure 4** summarizes the state of the GOOS in March 2018 (Note that the small size of the figure gives the impression that the ocean is full of such observations; in fact, the spacing between measurements ranges from 3 to 5 degrees). Major contributions to the GOOS include: the Argo profiling float array of close to 4,000 floats; moored and drifting buoys, sustained time series sites, usually moorings coordinated by OceanSITES; ship-based repeat hydrography through GO-SHIP; shipboard sampling along lines repeated every 5 to 10 years; tide gauges; and ocean and meteorological sampling from merchant ships.

To a large extent the work to develop a GOOS was motivated by the need to better understand the role of the ocean in climate and to develop improved predictability at interannual and longer time scales.

The Motivation for the Present Approach to Sustained Ocean Observing

Sustained and uninterrupted ocean observations are vital to understanding the state and trend of many physical, chemical, and biological components of the Earth system. The ocean has absorbed 90% of the surplus heat (Rhein et al., 2013) and about 30% of the excess CO_2 released by anthropogenic activities (Ciais et al., 2013). It receives close to 100% of the freshwater lost from land ice. The deep ocean is a long-term reservoir of these components, and observations must occur over long time scales to capture this. Time series of observations need to be collected at a frequency sufficient to capture subseasonal, seasonal, and longer time scale patterns. Gaps in observations, once lost, cannot be restored. The NASEM 2017 report, for example, identifies the value of ocean observing in closing three global budgets for climate: heat, carbon, and fresh water. Changes in the Earth's climate also threaten ocean ecosystems. In order to track the impact of the changing climate on ocean biodiversity, observations are critical. Notably, coral reefs and shellfish are impacted by increasing acidity of the ocean and warming waters alter and reduce the range of valuable fisheries species.

Sustained ocean observations are also critical for understanding and predicting phenomena beyond climate that have consequences for the economy and society. The same platforms that provide critical climate information can be used to provide a broader set of benefits. Foremost, modern weather forecasting, including hurricane formation and intensity as well as seasonal precipitation, is reliant on temperature and current observations in the ocean. The Tropical Pacific Observing System (TPOS), which measures long-term changes in ocean-atmosphere heat exchange, was originally designed to better understand and predict the El Niño–Southern Oscillation (ENSO) phenomenon. TPOS has provided vital data to improve ENSO forecasts for decisions about agriculture, for example (Hansen et al., 1998; Chiodi and Harrison, 2017). Following the TPOS model, ocean observing systems have been developed for the Atlantic (PIRATA) and Indian Ocean (RAMA).

Progress in the Present Observing System

A wide variety of institutions and sectors have participated in the development of the present international ocean observing enterprise. Ocean observing is an end-to-end system, consisting of engineering, operations, data management, information products, and workforce, supported by planning and governance at national and international levels. The global observing system that stands today is the result of an internationally coordinated set of organizations and platforms. Global observations are coordinated under GOOS, an organization

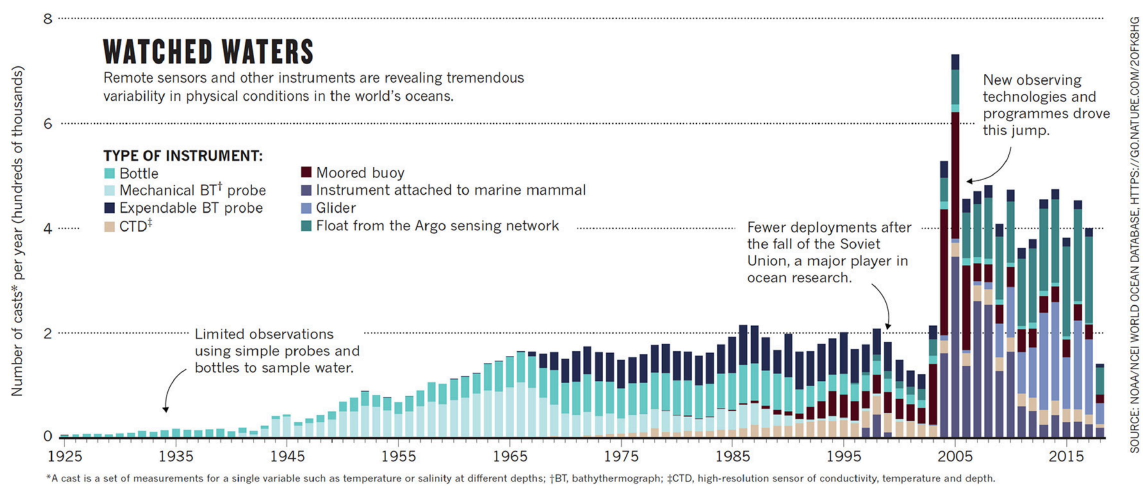

FIGURE 3 | The growth of the number of temperature and/or salinity profiles per year since 1925. The type of data is coded by the colors. Relatively steady levels of ocean sampling held from the mid-1960s to the mid-2000s, when new technology roughly doubled the number of profiles obtained from near 200,000 per year to 400,000 per year. Figure from Bates et al. (2018).

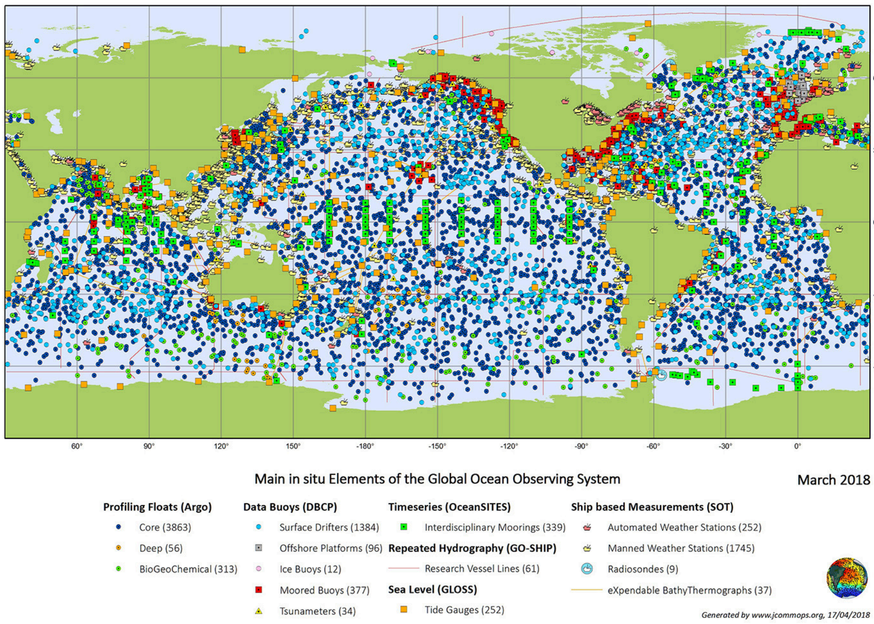

FIGURE 4 | The status in March 2018 of the elements of the GOOS, as tracked by the Joint Technical Commission on Marine Meteorology (JCOMM)[8]. Updated monthly summary maps available at JCOMM, 2018 (http://www.jcommops.org/). The dots representing platform locations are sized to be visible, but the actual coverage of the ocean remains sparse.

of the Intergovernmental Oceanographic Commission (IOC). GOOS supports observations in three thematic areas: Climate, Operational Ocean Services, and Ocean Health. Implementation of the global observing system is guided by the Framework for Ocean Observing (FOO; Lindstrom et al., 2012), a science-driven process for identifying priority observations and requirements that address societal needs. Ocean observations are also one component of climate observations organized under the Global Climate Observing System (GCOS). GOOS and GCOS are supported by expert panels that develop standards for observations of variables, the Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs), respectively. The Ocean Observations Panel for Climate (OOPC) is the expert panel for physical variables. The FOO allows the ocean observing system to evolve based on technology advances and emerging research needs, strengthened by input from expert panels and other scientific associations, as well as the research community as a whole.

GCOS and GOOS draw on the expertise of the oceanographic and climate science community to advise the implementation of ocean observations. The development of observing requirements for EOVs and ECVs is guided by expert panels. EOVs (and the ocean-based ECVs) fall into three categories, with associated panels: Physics, Biogeochemistry, and Biology and Ecosystems. For example, the Physics panel built on the pre-existing International Ocean Carbon Coordination Project (IOCCP), which promotes and coordinates ocean carbon observations. Another important entity for facilitating observations, analyses, and predictions of changes in the Earth's climate system is the World Climate Research Program's (WCRP) CLIVAR (Climate and Ocean: Variability, Predictability and Change). CLIVAR also carries out short-term, intense sampling during process studies. The role of the WCRP and of the expert panels such as the OOPC are discussed in related OceanObs'19 papers.

Many nations now contribute to sustained ocean observing. Within the United States, Federal agencies engage in the intergovernmental negotiations at the international level, and are the primary supporters of ocean observing activities through funding for research, technology, and operations. Key agencies include the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Office of Naval Research (ONR). Federal activities are coordinated through subcommittees and interagency working groups under the National Science and Technology Council. Federal agencies fulfill their contribution to GOOS through the U.S. Integrated Ocean Observing System (IOOS). Federal and nonfederal contributions to IOOS are organized by NOAA in consultation with the Interagency Ocean Observations Committee (IOOC), which conducts the activities related to IOOS planning, policy, and coordination. Agencies can cooperatively fund ocean research through the National Ocean Partnership Program (NOPP) and coordinate through the National Ocean Research Leadership Council. For instance, NOPP facilitated the partnership between the U.S. Navy and NOAA in the development and implementation of the U.S. Argo program and ocean prediction systems with the HYCOM

[8]http://www.goosocean.org/index.php?option=com_content&view=article&id=21&Itemid=271

modeling initiative. Furthermore, NOPP facilitated public-private support from NSF and the Packard Foundation for development of the Environmental Sample Processor—an important advance in automated water sampling for molecular approaches to biological monitoring, such as eDNA applications, as well as development of other new platforms and sensors (Lindstrom et al., 2009). NOPP supports the Marine Biodiversity Observation Network (MBON), which provides a portal for biodiversity information, including eDNA and more traditional datasets (http://www.marinebon.org/our-work.html). The track record of NOPP provides useful lessons that could inform the development of public-private partnership organizations in other countries.

In many ways, **Figure 4** represents a remarkable achievement in the creation of a new observing system. However, financial pressures on the nations and national agencies providing the on-going support are evident. For example, NOAA's IOOS Regional Observations and Sustained Ocean Observations and Monitoring programs have been essentially flat-funded over the past 5 years. Sustained Ocean Observations and Monitoring, which funds the U.S. Argo, would suffer an 11% decrease if the President's FY 2019 budget is enacted (NOAA, 2015, 2018b). At present, there is a study of the TPOS aimed at examining how to go forward with reduced contributions to the array; and some nations have terminated elements of observing arrays, such as the Southern Hemisphere sites of NSF's Ocean Observatories Initiative.

Ocean Data in the Hands of Users

The value of sustained observations is only realized when data and derived information products are made available to users. Data collected under GOOS are made freely available for users through Data Assembly Centers (DACs). DACS also play a role in unifying various data streams being collected. However, at present, global distribution of data in real time is limited. Data must be collected from a variety of DACs, dependent on the platform it was collected from. Additionally, many users are not traditional users of NetCDF or ASCII data formats. There is an opportunity to increase data access globally.

Additionally, there is a need for frameworks to synthesize data from diverse sources in order to develop data products that provide more detailed knowledge of the Earth system. Data assimilation models have been developed for weather prediction, and are gaining use for a broader range of consumers. The sparsity of ocean observations has made implementation of data assimilation frameworks difficult. Continuous global ocean observations are needed to develop robust data products for predicting weather, climate trends, and other uses.

Challenges of the Present and Future Opportunities

The NASEM 2017 report highlighted several challenges facing sustained global ocean observations. The readiness of biological and ecosystem observations lags behind those for physical and biogeochemical variables. Some important processes are insufficiently measured, such as fine scale mixing. The deep ocean is a long-term reservoir of heat and carbon, but few platforms reach these depths to allow quantification. There is also a lack of consistent deployment of observing platforms within Exclusive Economic Zones (EEZs). About 30% of the global ocean lies with EEZs and other maritime zones, and thus, deployment in these zones is necessary for global coverage. This will require participation from and partnership with many nations. However, lack of trained personnel, particularly in developing countries and nations with economies in transition, limits expansion of a globally coordinated observing system (POGO (Partnership for Observation of the Global Oceans), 2018). Initiatives to build capacity globally have played a role in involving a greater number of countries in ocean observing implementation and planning. One example of the type of programs that have been effective in supporting capacity building for ocean observing is the Partnership for Observation of the Global Oceans (POGO). Another example is the International Oceanographic Data and Information Exchange Programme (IODE) which promotes collection, exchange, and access to oceanographic data and information, in part by assisting nations in acquiring the expertise to become partners in IODE and support the Framework for Ocean Observing (IOC-UNESCO, 2017).

To illustrate the challenges, we note that in the U.S., federal and academic research institutions oversee a significant portion of the national contribution to the global observing system. This workforce provides the engineering, technical, and research expertise to improve, implement, and create data products for the ocean observing enterprise. Some nonprofit and philanthropic organizations support ocean observing by providing funding for conservation research and technology. Private companies play a role developing technology and data tools, as well as serving as a user of observational data and data products. Coordination across this range of stakeholder is vital for advancing ocean observing. However, within the United States, government agencies are the primary source of support, and challenges in sustaining funding for ocean observing threaten U.S. contributions and threaten the stability of consistent data collection. Annual budget cycles and short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.

The ocean is a physically harsh and logistically complex environment for the collection of observations. Observing platforms corrode in seawater, are subject to biofouling, and must withstand cold water and high pressures. Seawater is opaque to radio frequencies, making remote communication of data difficult. Platforms rely on low-powered, durable electronics so they may last for long periods in remote areas of the ocean without maintenance. Current and near-future technologies, particularly related to batteries and autonomous platforms, have helped address ocean observing challenges. However, U.S. investments in technology have diminished since the 1980s. Despite expected advancements in technology, global and ocean class ships will be necessary to maintain platforms and collect some types of observations. A decreasing national fleet puts this capability at risk.

Gaps remain in the current observing system that must be filled, such as data-sparse regions in the Southern Ocean and Southeastern Pacific. Some observations, like ambient noise, which includes signals from wind and rain as well as from marine organisms, human activities, and other sources, are not now commonly collected but in the future passive acoustic sensors could be deployed on may platforms. With sufficient support in the future, ocean observing programs will evolve as improvements in technology increase observing capabilities, and as changes in the Earth system necessitate new observing requirements. Increasing ice-free summers in the Arctic Ocean, for example, will open up more surfaces to be monitored. The GOOS expert panels, including the OOPC for physics and the biogeochemical and the biology and ecosystems panels, will continue to guide the development of the observing system under foci that are primarily driven by science, including climate. International and national research programs, including the WCRP, CLIVAR, and others, will contribute advancements in technology and knowledge that will also guide the evolution of the observing system. The resulting desire to sample with new sensors that require additional power and platforms further challenges the present efforts.

THE FUTURE: AN OCEAN PARTNERSHIP FOR SUSTAINED OBSERVATIONS AS A COLLECTIVE IMPACT ORGANIZATION

The development of sustained ocean observing for climate has had success, but now faces challenges and future growth is uncertain. Adding on the broader needs presented in Section The Social and Environmental Landscape, we believe that a new strategy is needed and present a proposal for an Ocean Partnership for Sustained Observations.

As part of a new approach, a long-term plan, with a framework for partnerships with stakeholders, is needed. The NASEM 2017 report identifies the value of a formal partnership to increase engagement and coordination of the ocean observation science community with nonprofits, philanthropic organizations, academia, U.S. federal agencies, and the commercial sector. The importance of ocean data for national security, the economy, and society, as well the international coordination required to support a global system, makes the federal government primarily responsible for supporting ocean observations. However, there is an opportunity for new models of support of a sustained observing system within and beyond federal structures.

Long-term planning and partnerships with private and nonprofit sectors could address some of the challenges in maintaining sustained observations nationally. This includes support for workforce, technology development, deep ocean moorings and global and ocean class ships. Shell's Stones Deep-Water Project is a recent example of a partnership to collect long-term deep ocean data that utilizes infrastructure for oil and gas development for ocean observing. Current collaborators with Shell on the Stones Metocean Observatory Project include the University of Southern Mississippi, Texas A&M University, Fugro, the National Oceanic and Atmospheric Administration, and the NASEM Gulf Research Program (http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=11142018).

There is a challenge in supporting early technical, engineering, and research staff. Metrics for academic promotion such as a large number of publications are not aligned with the long-term nature of ocean observing, particularly for climate. Observational data for climate takes years to collect, and because it is often made freely available, young scientists have little incentive to initiate or sustain long time series given the career demands for rapid publication of novel research results Scientists are also hindered by the lack of research positions that provide long-term funding stability. This threatens the continuity of the workforce to sustain ocean observing in the future.

Bringing Users Together Under Shared Values

What is needed for the future? Governance and protection require all relevant players to be at the table for policy decisions. Policy decisions must be underpinned by the right science and smart, innovative financial models. Partnerships and collaborations within and between nations are central to success. Enforcement is essential. A new model of successful international governance is one that is fed by science and supported for implementation not only by policy makers but also by business executives, local communities and financial institutions.

New Paradigm for Support of Sustained Ocean Observations

The Need for a New Cooperative Approach

As mentioned at the beginning, while the NASEM 2017 report specifically suggested an Ocean Climate Partnership, it is clear now that to achieve the Blue Economy and support the growing breadth of ocean activities and interests, it is more appropriate to build toward a broader international Ocean Partnership for Sustained Observing (OPSO). Such a partnership would be an effective mechanism to increase engagement and coordination of the ocean observation science community with non-profits, philanthropic organizations, academia, U.S. federal agencies, and the commercial sector. Through their shared interests in the observational data and associated products, the OPSO members would work together toward the goal of sustaining an ocean observing system for climate and other sustainability purposes.

But to get from here to there will require new cooperation beyond what has been achieved to date. Up to recently, the many ocean organizations that do exist have tended to operate more on their own than jointly. Just one illustrative example can be seen with the broad mandate of the UN, which covers ocean science, shipping, dumping, biodiversity, fisheries, mining, the Arctic, and more (**Figure 5**). This broad mandate emphasizes the importance of new and growing uses of the ocean.

NGOs such as Oceana, World Wildlife Fund, Conservation International, and many others have developed effective programs and are strong on raising awareness. Foundations have tended to focus on a narrow range of internal interests and the private sectors works within the scope of specific business models. But there is increasing awareness of the need for more data from all of these sectors. For example, the World Economic Forum's World Ocean Forum has already stated that: "We need

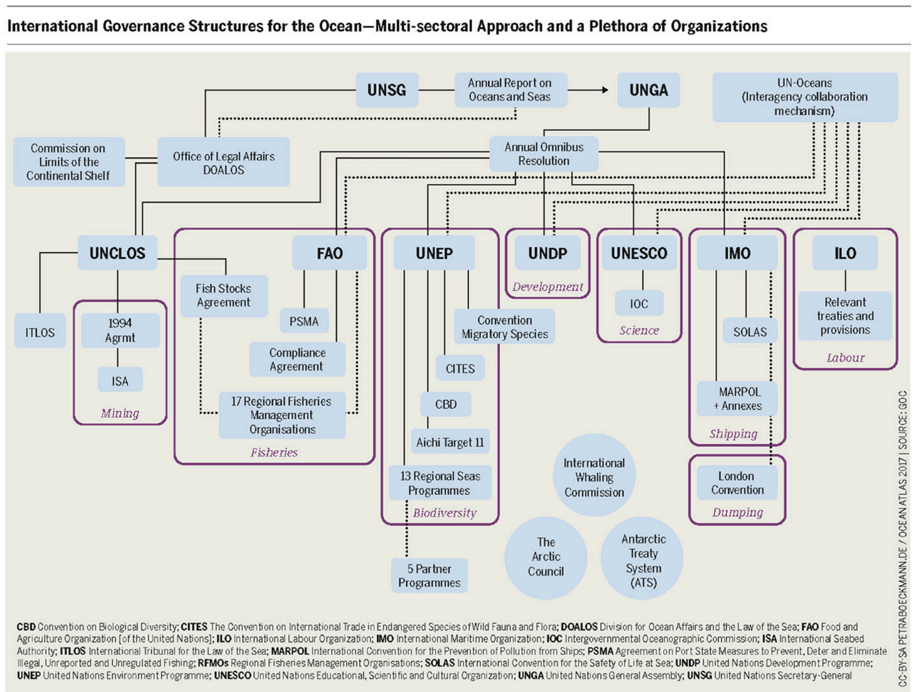

FIGURE 5 | UN Mandates for Ocean-Related Activities (UN Ocean Structure Atlas, 2017)[9].

much more data at higher frequency, quality, and variety to understand our oceans to the degree we already understand the land. Less than 5% of the oceans are comprehensively monitored. We need more data collection capacity to unlock the sustainable development potential of the oceans and protect critical ecosystems." (World Ocean Forum, 2017) [10]

We want to focus here on how best to bring these many interests together and move forward on stronger support for ocean observations. Below we outline the collective impact approach, then show some examples of collective impact organizations that have been successful, relate these ideas to existing atmosphere and ocean organizations, and conclude with ideas for the Ocean Partnership for Sustained Observations.

The Collective Impact Organization

An important emerging concept is that of the *collective impact organization* approach to address broad issues with many constituencies. This new approach arises from the realization that the complex nature of most social problems makes it difficult for any single program or organization, however well managed and funded, to single-handedly create lasting large-scale change. In such collective organizations, the participants share a vision of change and a commitment to solve a problem by coordinating their work and agreeing on shared goals. Participants agree to shared core values and agenda, share metrics for success, support mutually reinforcing activities, provide continuous communication, and have an agreed-on backbone support organization (**Figure 6**).

In such an organization, the *shared agenda and set of core values* should be initially established by the contributing organizations. The shared agenda should be broad enough that different contributors will contribute in very different ways to an overall effort yet provide boundaries that ensure the effort is overly ambitious. For ocean observations, examples of shared values might include "sustained observations," "open access to data," or "observations for the benefit of society." Such core values should be decided upon by the community of contributors and should involve listening sessions within the various contributing and stakeholder communities. These core values provide guidance for a shared agenda, and a platform for defining metrics of success.

Shared metrics of success provide an opportunity to evaluate whether actions taken by the organization (or contributing organizations) are contributing to the overall agenda, despite unique contributions from each of the contributors. For example, a core value of "open access to data" suggests that a metric of success would be the amount of collected data that is easily accessible. While each organization may have different objectives, it is important that a broad enough set of metrics exist that each organization can determine and evaluate its contribution to the overall effort. These metrics are decided upon by the advisory boards, but should be collected by the backbone organization.

In order for collective impact to be greater than the sum of its parts, coordination is needed to ensure

[9]https://www.boell.de/sites/default/files/web_170607_ocean_atlas_vektor_us_v102.pdf?dimension1=ds_ocean_atlas

[10]https://medium.com/world-ocean-forum/how-data-can-heal-our-oceans-e80a3e817b22

The Five Conditions of Collective Impact	
Common Agenda	All participants have a shared vision for change including a common understanding of the problem and a joint approach to solving it through agreed upon actions.
Shared Measurement	Collecting data and measuring results consistently across all participants ensures efforts remain aligned and participants hold each other accountable.
Mutually Reinforcing Activities	Participant activities must be differentiated while still being coordinated through a mutually reinforcing plan of action.
Continuous Communication	Consistent and open communication is needed across the many players to build trust, assure mutual objectives, and create common motivation.
Backbone Support	Creating and managing collective impact requires a separate organization(s) with staff and a specific set of skills to serve as the backbone for the entire initiative and coordinate participating organizations and agencies.

FIGURE 6 | A summary of the five conditions they listed to be met for a collective impact organization. From Hanleybrown et al. (2012).

that different *efforts are mutually reinforcing*. For example, needs for new oceanic parameters to be measured for scientific discovery may motivate research and development of new instrumentation by private business. The organization should look to capitalize on these feedbacks between activities of the different contributing organizations.

Continued communication is necessary for buy-in among the different organizations, and to provide a sense of legitimacy to the various communities that are being served by the organization. There should be several layers of communication here. The first is at an advisory level, through established advisory boards that adjust the shared agenda, and set strategic planning goals. A second level of communication is required among the different participants in the organization to ensure coordination between efforts. And a third level of communication is outward facing, and ensures that efforts of each participating organization, as well as the effort as a whole, are being communicated to the broader communities and stakeholders that are served by the activities of the organizations.

Finally, it is important to emphasize that the *backbone support organization* is key to the success of efforts at developing collective impact. The importance and role of the backbone organization is outlined in papers by Turner et al. (2012), and include guiding the vision and strategy, coordination and support for the aligned activities, tracking metrics of success, communicating results, and mobilizing funding. While the backbone organization is critical for carrying out the vision and strategies, it should not dictate the agenda or the core values (though membership should be involved in such discussions). The backbone organization also serves to facilitate communication at various levels (described above).

Examples of Successful Collective Impact Organizations

We believe that the general concepts of collective impact organizations can be applied in the ocean observations context, and provide here two examples of collective impact organizations that show how the concept can be effective both with programmatic institutions and with philanthropies.

Wisconsin Initiative on Climate Change Impacts (WICCI)

The Wisconsin Initiative on Climate Change Impacts (WICCI, 2018)[11] was founded consistent with collective impact principles to deal with the fact that climate variability and change impact society in ways that can rarely be understood with a disciplinary, or linear approach. It arose from the need for interdisciplinary settings in which interactions between different disciplines are necessary for defining disciplinary knowledge gaps, addressing those gaps, and assimilating information in order to address specific problems.

WICCI's organizational structure follows very closely the literature on Collective Impact Organizations (Kania and Kramer, 2011) and complex-adaptive systems. Consistent with collective impact, WICCI is a broad, semi-open, decentralized network that is served by a centralized, non-prescriptive infrastructure. This approach is especially powerful because it is inclusive (the open network approach), adaptive (as new research needs emerge WICCI easily connects with existing expertise), and preserves autonomy of the participating individuals and groups (this avoids issues of "territory" and attribution). It is also important to note that WICCI exists as an organization within a constantly evolving complex adaptive system. In such a system, one role of the organization is to ensure that new ideas and needs are identified and communicated within the

[11] http://www.wicci.wisc.edu/

network and with relevant outside expertise (Rammel et al., 2007). WICCI accomplishes that role using a variety of methods across a hierarchy of scales that follow many of the ideas found in research on complex adaptive systems and collective impact. Ultimately, WICCI has been very successful in enabling climate adaptation in Wisconsin and the region, including contributing to K-12 educational materials, developing decision support tools for coastal management, evaluating infrastructure decisions for storm water management, community planning, providing a scientific basis for WDNR land priorities, and much more.

Experience with WICCI has shown that any broad-scale effort should be inclusive of existing disciplinary and interdisciplinary research and decision-making activities, and should bring value to those efforts. It emphasizes that no single approach is optimal for addressing specific climate impacts. Instead, it focuses on a diverse set of approaches that allow specific efforts to move forward in ways that best meet the needs and constraints of the situation.

ClimateWorks

ClimateWorks (2018)[12] is an example of an organization that sees itself as a "catalyst for collective impact." It was established in 2008 by the William and Flora Hewlett Foundation, the David and Lucile Packard Foundation, the Energy Foundation, the Doris Duke Charitable Foundation, the Joyce Foundation, and the Oak Foundation to explore how philanthropy could have greater impact in the effort to mitigate dangerous climate change (see ClimateWorks., 2008). That report identified priorities for intervention globally and charted a course for climate philanthropy. During the first 6 years, ClimateWorks made hundreds of grants worldwide, helped build capacity in key regions, and collaborated with a network of partners to support research, policy advocacy, outreach and public engagement, all with the aim of reducing the emissions that cause climate change. These successes confirmed that strategic philanthropic investments could help shape public policy, private sector engagement, and public support, hereby helping to reduce carbon emissions, at scale. ClimateWorks' global scope and focus on key regions were also important strengths.

In 2013, ClimateWorks began to engage with broader networks of partners, share strategies and knowledge more widely, and support more coordination among funders. The group took on a bigger role to help leading climate funders coordinate and worked with partners around the world to grow climate philanthropy and reduce the emissions that cause climate change. ClimateWorks shows how the collective impact approach can have an important impact on society's need to move toward a prosperous, sustainable, low-carbon future.

Some Existing Meteorological and Oceanographic Organizations Considered in the Context of a Collective Impact Organization

Existing coordinating bodies

In the U.S., organizations to support ocean observations can be traced back to the 1990s with the development of the U.S. contribution to the nascent GOOS. In 2000, the Ocean.US office was established to support development of the national ocean observing system. These early efforts gained traction after a workshop at Airlie House in 2002 that coalesced around a vision for an Integrated Ocean Observing System (IOOS;Ocean US, 2002). The vision identified 7 areas of societal benefit that would guide IOOS:

- Detecting and forecasting oceanic components of climate variability
- Facilitating safe and efficient marine operations
- Ensuring national security
- Managing resources for sustainable use
- Preserving and restoring healthy marine ecosystems
- Mitigating natural hazards
- Ensuring public health

Since then, U.S. IOOS has developed into two components: the US contribution of open ocean observations to GOOS and a domestic coastal program. The latter is organized as a national-regional partnership that works "to provide new tools and forecasts to improve safety, enhance the economy, and protect our environment." In 2009, IOOS became authorized under the Omnibus Public Lands Management Act and the program office was established in NOAA's National Ocean Service, becoming the official U.S. IOOS program office in 2011. Through the national-regional partnership, each region develops a program of observations to address local needs within standards set by the national program.

The IOOS Association, formerly known as the National Federation of Regional Associations for Ocean and Coastal Observing (NFRA), provides an example of a non-governmental, non-profit organization formed to advance ocean observing efforts, in this case for the coastal ocean observing programs run through a regional-national partnership. The IOOS Association has been an important part of the progress made in implementing IOOS. Early organizers of the regional programs recognized that the need to organize themselves to promote collaboration, communication, and integration, and to develop a collective voice to support the national commitment to the program. Therefore, this association of the regional programs represents a type of collective impact organization that pools the shared interests and energies of the individual regional programs in support of US IOOS. The IOOS Association includes 11 IOOS Regional Associations (http://www.ioosassociation.org/about)

Other oceans groups that have contributed to the development and support of ocean observing systems include POGO, made up of representatives from major ocean institutions from around the world, and the Consortium for Ocean Leadership, an organization that advocates for ocean science and technology with a membership of predominantly academic institutions, but with important representatives from industry, aquaria, and non-profits.

The global weather enterprise (GWE)

A useful analog for the ocean observing community is the Global Weather Enterprise which provides for daily weather forecasts and much more for the world. Although not

[12]https://www.climateworks.org/about-us/our-history/

designed as a Collective Impact Organization, it has many of the same characteristics. In the Enterprise arrangement, the public, private and academic sectors cooperate for mutual benefit. This Enterprise is most mature in the U.S. where the American Meteorological Society has played an important role as a neutral host for discussions and planning to further the enterprise (see AMS, 2017)[13] The scope includes observations, forecasting services, business development, and policy development. Examples of tangible benefits of the Enterprise include private companies lobbying to maintain observing infrastructure, seamless cooperation in severe weather events, technology transfer, and broader career opportunities for students.

In recent years, the UN World Meteorological Organization has been promoting the Global Weather Enterprise. The urgency to do this comes from the need to be even more effective in saving lives and protecting infrastructure because of vulnerability to weather hazards in a changing climate and the rapid advance of technology that is more readily adapted by private companies. All participants in the Enterprise recognize there is a strong need for more science, observations, and computing power to improve weather forecasts. Moreover, the context for the weather enterprise is evolving rapidly today as improvements in technology, including those driven by other industries, are creating exceptional opportunities to deliver even higher quality weather forecasts. Continuing public sector investment in both weather science and in the global observing system is viewed as essential (WMO, 2016).[14]

Just as the Global Weather Enterprise supports many different needs, the global ocean observing systems must support many different needs. And just as the Global Weather Enterprise builds strong collaboration and has good support from both the public and private sectors, global ocean observing systems must also look for increased collaboration and diverse funding. It is the combination of needs, ranging from science and understanding to all of the data needed to bring sustainable management to ocean resources, which must be mobilized to support the ocean observing system. Could there be a Global Ocean Enterprise?

Public-Private Partnerships

Today we are seeing new private sector coalitions and public-private partnerships being formed. In general, ocean organizations are beginning to find that more collaboration and joint projects are more effective in accomplishing real results. Two useful examples are the *World Ocean Council* and the *World Economic Forum's New Vision for the Ocean*. The World Ocean Council was founded in 2008 as global, cross-sectoral ocean industry leadership alliance to bring together leaders of corporations, industry and trade associations, as well as research, academic, and scientific institutions with a commitment to the future of the ocean (World Ocean Council, 2017).[15] The WOC is committed to corporate ocean responsibility and is taking a multi-sectoral approach to address cross-cutting issues affecting ocean sustainable development, science, and stewardship of the seas. The interests of the WOC members shows its breadth: shipping, oil and gas, fisheries, aquaculture, tourism, renewable energy (wind, wave, tidal), ports, dredging, cables, as well as the maritime legal, financial and insurance communities, and others. They have a commitment to ensuring that the ocean business community's role in ocean sustainable development is understood by all relevant stakeholders (decision makers, policy makers, intergovernmental bodies etc.).

The World Economic Forum's New Vision for the Ocean (NVO) project (World Economic Forum, 2018)[16] supports a range of initiatives and events from the public and private sectors to ensure the long-term sustainable use of the ocean. Designed to help advance SDG 14, the New Ocean Vision offers a platform for key industries to work together with government, civil society and the scientific community on implementation and accountability. It has three primary objectives through 2020: (1) work with the UN to help shape and drive an action track for SDG 14, (2) Mobilize a cross-sectoral "Friends of Ocean Action" group to advance the Ocean Action Track, and (3) Mobilize additional finance in support of the Ocean Action Track by identifying and pursuing funding from philanthropic organizations, donor agencies and high net worth individuals in support of the Ocean Action Track.

An interesting analog for what the ocean community might try to do is Mission Innovation, a clean energy venture launched at the Paris Climate Conference in 2015. The program is a global initiative of 23 countries and the European Union, representing 70% of the world's GDP and 80% of government investment in clean energy research. The members of Mission Innovation have committed to taking action to double their public clean energy over 5 years. To that end, Mission Innovation members are encouraging collaboration among partner countries, share information, and coordinate with businesses and investors. Mission Innovation is complemented by private sector-led investments in clean energy, focusing on early-stage innovations (Mission Innovation, 2017).[17] Several multi-million dollar programs are in the works.

As the UN agencies and the ocean community build momentum for the UN Ocean Conference in 2020, it would make sense for the Ocean Partnership for Sustained Observations to explore similar options to Mission Innovation for linking to the private sector.

It will be important to invite these new private sector groups to coordinate with existing groups noted above such as IOOS, the Consortium for Ocean Leadership, CLIVAR, POGO, and others. This will build a full set of users to strengthen coordination and to fund and implement an enhanced ocean observing system.

We envision the Ocean Partnership for Sustained Observations as a collective impact organization. It would bring together the main partners now involved in ocean observations, and the key users. Given the extensive work that has already been done on science and essential ocean

[13] https://www.ametsoc.org/cwwce/

[14] https://public.wmo.int/en/resources/bulletin/weather-enterprise-global-public-private-partnership

[15] https://www.oceancouncil.org/

[16] https://www.weforum.org/projects/a-new-vision-for-the-ocean

[17] http://mission-innovation.net/

observations, the focus of the Partnership would be on funding and implementation. Here we focus on new opportunities for cooperation and funding.

The Ocean Partnership for Sustained Observations—A Focus on Coordinating Funding and Resources

Real progress on any of the issues discussed in this white paper requires a combination of improved coordination among users, continuation of existing funding commitments, and new resources for essential enhancements of the observing system. The NASEM 2017 report has underlined the importance of substantial institutional support and the need for guarantees of long-term funding. But, it also notes that overall funding has been flat for about a decade. It points out that annual budget approvals, unpredictable funding streams, and short-term grants are already leading to discontinuity of measurements. Better coordination among users and additional funding from a variety of sources will be required to overcome these difficulties.

Up to now in the U.S. (and in most other countries), federal agencies have been the primary supporters of ocean observing activities, with some notable exceptions, e.g., the $4 million support of Deep Argo float deployments from the Paul G. Allen Philanthropies and some nonprofit funding for ocean conservation research and technological development. But few non-governmental organizations have provided funding to sustain long-term projects such as ocean observing activities. A partnership organization would build constituencies and provide a venue for identification of priority efforts to direct resources. Here we list some of these opportunities from working across sectors.

The international Ocean Partnership for Sustained Observations (OPSO) could play an important role in helping determine what programs and institutions are required for long-term observations. But to be successful it will have to do more than that. It will have to be active in establishing stronger coordination, identifying financial needs, and raising and finding funds for the necessary institutions and programs. The collaborative structure of the OPSO ensures that the representation is comprehensive and that activities will be done with full knowledge of existing institutions and programs.

While identification of coordinated uses for existing funding will be a significant step, there is also a role for a fund-raising focus, probably with a designated "Advancement" or "Development" office.

We have outlined above the needs for expanding ocean observations to a much wider group of users who are looking to the ocean for more resources from fish to mining and from generating clean energy to finding new genetic resources. Dealing with climate change, from warming to acidification, will require much better monitoring of life and physical properties of the ocean. The need for a broad approach means that ocean actors beyond national governments must be involved.

National Governments

There are two approaches to be considered here: first would be working with national governments that have demonstrated interest in expanding their ocean programs to meet national and global needs. Up to now, the U.S. has been the major financial supporter of *in-situ* and remote sensing ocean observations, but other nations also have strong programs. Expansion of ocean programs is happening in a number of countries, including for example, Germany and China, South Korea, Japan, and Indonesia. A direct approach to the ocean agencies in these countries would be the right way to start. Second would be to tackle the UN system, now recently focused on oceans working with the new UN Oceans interagency mechanism that is looking to enhance the coordination of the relevant UN bodies, of which there are many. A careful study of this new coordination could yield information about where in the system a long-term observation program might find traction (beyond UNESCO/IOC, already fully aware of the needs).

Philanthropies

Philanthropic efforts have in part filled gaps in institutional support for projects. The OPSO could follow up on the NASEM 2017 report, which suggests "synergistic coordination," including asking foundations to perhaps offer guidance for structuring sustained observation programs. Here the leadership of the OPSO should work directly with the leaders of the philanthropies. For projects, the OPSO should identify a small number of people who could analyze which projects are currently active, and possibly identify where ocean observations could help meet foundation needs. The organization "Funding the Ocean.Org" (Funding the Ocean.org, 2018)[18] provides information and a map of where a number of foundations are funding projects, mostly focused on conservation issues.

Nonprofit, Non-governmental Organizations

The ocean observing community has much to offer the conservation community, showing how new technology can provide better and longer-term data to improve the success of conservation activities. It would be useful to start a dialog with organizations like World Wildlife Fund, Conservations International, Oceana, and the Nature Conservancy to see if they would like to collaboratively develop an approach for more comprehensive observations. The Nature Conservancy's Ocean Wealth report gives many examples of where such a collaboration could begin (The Nature Conservancy, 2017).[19]

The Private Sector

Three aspects of engagement of the private sector through OPSO are through (1) collaboration with resource extraction companies to include observations as part of their practices, ranging from oil and gas exploration and operations to deep-sea mining activities, (2) coordinating on applications for new technologies and instruments, and (3) support from corporations using long-term ocean data and information to help their corporate products. Examples of the first are the desire of oil companies to find resources and to protect the ocean from spills and blowouts and the need to monitor possible deep-sea mining activities for the long-term. An example of the

[18] http://fundingtheocean.org/resources/
[19] http://maps.oceanwealth.org/

second is the rapidly growing autonomous vehicle industry led by the private sector but providing value for national needs (e.g., Saildrone). For the third, the logical group is the reinsurance companies whose forecasts rely partly on ocean data, as well as the private weather companies that are now getting into longer-range forecasting. The discussion needs to be how technology can help meet a bottom line, and help a company meet corporate sustainability commitments. There may be a good opportunity here for the OPSO to work specifically with the World Ocean Council (WOC) whose mission is to bring together the multi-sector Ocean Business Community to catalyze global leadership and collaboration in ocean sustainability and "Corporate Ocean Responsibility." The WOC provides responsible companies from the Ocean Business Community the ability to collectively address cross-cutting ocean sustainable development challenges and shape the future of the ocean by engaging and working with other ocean stakeholders.

NEXT STEPS

In short, we believe that more effective coordination will bring multiple constituencies together and motivate more strategic and potentially new funding. To that end, in this section we propose a series of next steps for developing a coordinated effort to bring a variety of potential stakeholders into an international collective impact organization that focuses on ocean observations. The section provides a summary of best practices in initiating collective impact organizations and suggestions on how the observations community might move forward with a collective impact approach. These next steps are not meant to be prescriptive of the organization's agenda and membership, but rather provides a guideline for how such an organization could begin.

Phases of Collective Impact

The steps outlined below are based on research documenting successful launching of a collective impact organization. Hanleybrown et al. (2012) outline three phases of development for collective impact organizations (**Figure 7**) and describe factors that enhance probability of success for these stages. These include an influential champion (or group of champions), adequate financial resources, and an urgency for change. All of these factors are present now, or could be, for enhancement of the ocean observing system. We note that these three phases need not proceed independently but will likely involve some iteration between different activities.

Establish a Group of Strong Supporters or Champions

The initial charge of this international group would be to develop a straw proposal of the group's agenda and scope (see section The Collective Impact Organization). The initial group should include representation from a diverse set of stakeholders. The group would ideally be coordinated by an established organization, to be determined by discussion, and should include initial high-profile partner organizations that are representative of the diverse set of potential contributors to the organization. The group should meet regularly to develop a proposed agenda and scope, and to identify relevant stakeholders for listening sessions.

The first step would be to identify interested individuals who represent a diverse set of interests who would be served by ocean observations, those who conduct them, and others as appropriate. One role of the initial group would be to identify who all needs to be at the table, and start contacting them to set up some initial meetings.

Mapping the Landscape Through Listening Sessions

Once an initial set of champions is convened, the group should set up listening sessions that identify and document needs of various communities. This also serves to map the landscape of the organization, and to better define boundaries for the agenda. These listening sessions might include "Town Hall" meetings at scientific conferences such as AGU, EGU, and AMS meetings, or ocean industry trade conferences and sustainable ocean meetings as well as direct contact with existing organizations related to the ocean observing system (GOOS, CLIVAR, organizational meetings for the Decade of Ocean Science 2021–2030, etc.).

Results from the listening sessions will provide information for the original group that will provide input on new members or changes to the agenda and scope. These listening sessions should also aim to identify a set of stakeholder advisors that will form an (or multiple) advisory committee to the collective impact organization.

Establish the Backbone Infrastructure

A critical component of collective impact organization is a backbone infrastructure that provides support for the activities of the wider effort. This backbone infrastructure provides a centralized support for the decentralized landscape of stakeholders involved in the organization. The support includes internal communication and coordination within the group (e.g., setting up meetings, coordinating communication, providing needed data), and outward communication and coordination (the initial listening sessions, and continued communication with relevant stakeholder communities.)

It is important to remember that the backbone infrastructure does not set the agenda or boundaries of the organization but is responsible for helping to carry out that agenda. The development of core infrastructure helps ensure that the program has a strong base.

Moving Forward to Future Modes of Support and Governance

The listening sessions proposed above could start with an initial workshop including, as noted above, representatives from the ocean science and meteorology community, the national and state governments, the private sector, foundations, and NGOs. To avoid an impossibly large meeting, two or three initial meetings might be considered. Examples of organizations that might be included are IOOS, CLIVAR, POGO, and maybe others from the ocean science community, and JCOMM for the ocean weather community; the World Ocean Council and the World Economic Forum for the private sector; the

Phases of Collective Impact

Components for Success	PHASE I Initiate Action	PHASE II Organize for Impact	PHASE III Sustain Action and Impact
Governance and Infrastructure	Identify champions and form cross-sector group	Create infrastructure (backbone and processes)	Facilitate and refine
Strategic Planning	Map the landscape and use data to make case	Create common agenda (goals and strategy)	Support implementation (alignment to goals and strategies)
Community Involvement	Facilitate community outreach	Engage community and build public will	Continue engagement and conduct advocacy
Evaluation and Improvement	Analyze baseline data to identify key issues and gaps	Establish shared metrics (indicators, measurement, and approach)	Collect, track, and report progress (process to learn and improve)

FIGURE 7 | From Hanleybrown et al. (2012), the phases of effort toward developing a collective impact organization.

foundations that have supported ocean observations (W. M. Keck Foundation, Paul G. Allen Philanthropies, etc.); and appropriate environmental organizations such as The Wildlife Conservation Society, Conservation International, and Oceana. This list is just indicative of the kinds of organizations that might be involved.

The purpose of this initial workshop would be to assess the level of interest from the various constituencies in developing a more formal arrangement. Funding for the initial activities of the collective impact organization could initially come from contributions from each of the parties involved.

Conclusion

The oceans, with 50 times as much carbon as the atmosphere, 1,000 times the heat capacity and 100,000 times as much water, clearly play a central role in the climate and habitability of planet Earth (Schmitt, 2018). In the end, society as a whole benefits from all the ways that comprehensive ocean observations contribute to economies and human well-being, including all of those nations, communities, and individuals who depend on ocean use and resources. From small island states to coastal nations to worldwide commerce and trading, an ocean whose resources are used sustainably provides a steady foundation for human health and wealth [see *Mapping Ocean Wealth* (The Nature Conservancy, 2017)].[19]

In the discussion above, we have outlined how the scope of ocean observations is changing and how new demands for ocean information are emerging with a wide variety of priorities and expectations. The way that oceanographers work is also changing, with an increase in decentralized efforts at tackling problems. But government funding for observations has remained flat. To achieve the required funding increases, we argue here for new, flexible and nimble organizations that capitalize on the collective interest in oceans.

The driver for all of this is sustainable use of the ocean and its resources, now a well-articulated UN goal. A network of long-term and comprehensive observations is required to meet that goal. Such a network of observations requires participation from all sectors of the ocean and atmosphere communities ranging from exploration to weather and climate forecasting to resource extraction. In the near term, one key opportunity lies in the plans of the United Nations for an ocean conference in 2020 to address protection of marine biodiversity in the high seas. Just as the 2015 Paris Climate Conference drew attention to climate change and resulted in key agreements, it is likely that the UN 2020 Oceans meeting could be a focal point for bringing attention to the need for comprehensive ocean observations.

An important part of the new international collective impact organization will be to bring in new users and new technology, helping to create a whole that is bigger than the sum of its parts, a nucleus that makes everyone more effective. We urge the ocean community to embrace this broader set of users to create a collective impact organization that will maximize the collaboration of ocean actors and to lay the foundation for continued and increased funding for the enhanced observations that are required.

MAKING OCEANOBS'19 A STEPPING-OFF MILESTONE

We propose that we begin work at OceanObs'19 toward a collective impact organization, the Ocean Partnership for Sustained Observations and that the immediate target is an initial workshop. The workshop could have two sessions, one a plenary with keynote presentations to galvanize and engage a diverse set of users of ocean observations. The second session would begin the work to develop the backbone organization and start progress toward the collective impact organization. Further milestones would be an initial meeting of the Ocean Partnership for Sustained Observations in 2020, potentially allowing a role in 2020 meetings such as the Conference of the Parties to the Convention on Biological Diversity and 2020 UN Climate Change Conference (COP 26). The Partnership would also seek a role in the UN Decade of Ocean Science for Sustainable Development (2021–2030).

A beginning is to coordinate existing efforts by bringing multiple constituencies together. By bringing together constituencies across different sectors, we can more clearly define problems that many constituencies face, that can be solved through collective coordination of observations. This can also motivate new funding via recognizing key problems.

The landscape is changing, creative new funding sources are emerging with a wide variety of priorities and expectations. The way that we do work is also changing, with the increase in decentralized efforts at tackling problems. We need to think about new, flexible organizations that capitalize on the collective interest in our oceans and in ocean observations. We need new, nimble organizations that interact with a wide range of stakeholders to produce a collective impact that is "more than the sum of the parts." We need engagement from private foundations, the private sector, and new constituencies that will benefit from sustained ocean observations. Coordination across many diverse groups will build a new, broader base of support. We have outlined our suggesting for such an effort herein. We propose an initial discussion at Ocean Obs'19.

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RW, DB, MG, SR, RS, ET, and DV: contributed to the drafting and revision of this paper.

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The ICES Working Group on Oceanic Hydrography: A Bridge From *In-situ* Sampling to the Remote Autonomous Observation Era

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The ICES (International Council for the Exploration of the Sea) Working Group on Oceanic Hydrography (WGOH) was established in the late 1970's with the aim of gathering experts in physical oceanography to provide regular science-based assessments of the North Atlantic hydrographical condition (basically termohaline fields). From the beginning, the WGOH has relied on repeated long-term *in-situ* sampling at key sites around the North Atlantic, the Nordic Seas and adjacent shelf seas. An annual Report on Ocean Climate (IROC), produced by the WGOH since the late 1990's, summarizes trends in regional hydrography and identifies patterns linking these changes across the North Atlantic. Regional analyses are prepared by local experts who are directly involved in the monitoring programs responsible for collecting data presented in the report. An interactive webpage created in 2013 allows users to browse and download data that inform the IROC. Within the last two decades the physical oceanography community has evolved quickly incorporating technological advances such as autonomous devices into classical *in-situ* sampling programs. The WGOH has embraced such technological developments without diverting focus from ongoing *in-situ* long-term monitoring programs. Having longstanding experience synthesizing data and expertise from a large number of operational programs spanning an extensive international footprint, the WGOH has a unique perspective to offer the global ocean observing community. Here we discuss how we might foster connections with ICES to benefit the GOOS (Global Ocean Observing System) community.

Keywords: ocean climate, hydrography, timeseries, *in-situ* sampling, periodical report, science to policy, North Atlantic

1. INTRODUCTION

Since its founding in 1902, the International Council for the exploration of the Sea (ICES) has aimed to *increase the scientific knowledge of the marine environment and its living resources and to use this knowledge to provide unbiased, non-political advice to competent authorities*[1]. Primarily focused in the North Atlantic, ICES consists of a network of marine scientists that seek to coordinate on ocean monitoring and research, with the aim of providing the best available science to decision-makers.

ICES internal coordination relies on a complex structure that builds on the work carried out by up to 150 Expert Groups (EGs). EGs gather scientists from different countries to address specific topics within the broad spectrum of marine science. EG members work throughout the year, typically meeting in person once per year to work through a series of assigned tasks. No financial support is provided by ICES for EGs, so members need to find funds from their home institutions or projects. This presents a challenge to members and can compromise engagement, especially in periods of scarce resources. However, the long-term continuity of most EGs indicates that the funds invested in their activities are beneficial.

ICES established the Working Group on Ocean Hydrography (WGOH) within this framework in 1976 (ICES, 1977) to further the work done by the Hydrography Committee on data management and to coordinate cooperative hydrographic research within the framework of the World Meteorological Organization (WMO). At that time, 15 years ahead of the creation of the Global Ocean Observing System (GOOS), ICES represented a major partnership within the ocean community and a valuable opportunity for international networking, thereby inspiring several physical oceanographers to join the group. A review of the WGOH activity up to 2009 is given by Holliday et al. (2010) within the framework of the Oceans09 Conference. Currently, the WGOH is composed of nearly 50 members from 35 institutions and 18 countries around the North Atlantic region.

The WGOH has been active, meeting on a yearly basis, for more than 40 years. During these four decades the way we observe ocean hydrography has changed profoundly, evolving from primarily traditional vessel-based *in-situ* sampling to progressive incorporation of remote autonomous observation technologies. Also, the ocean observing community has grown, initiatives promoting international coordination have emerged, and comprehensive near-realtime ocean state analyses have been established as a public service. Meanwhile, the WGOH has continued to evolve while preserving the essence of its work aimed at providing ICES with information on ocean hydrography as a basis for marine ecosystems research and resources evaluation. Next we present our view on the future of the WGOH, highlighting its long-standing foundation which is rooted in international cooperation.

[1]from www.ices.dk/explore-us/what-we-do/Pages/default.aspx

2. OCEAN CLIMATE STATUS. THE IROC

A central component of WGOH annual meetings since its formation has been a session devoted to regional reviews of ocean climate. These reviews are based on data from existing monitoring programs run by individual countries or as international collaborations, sometimes in the framework of fisheries management programs. Considered together, the detailed regional reviews inform our understanding of North Atlantic variability and may be used to develop joint strategies for global monitoring.

Over time it became clear that this joint review of ocean status was valuable to other expert groups working on topics related to marine environment and ecosystems under the ICES umbrella. In 1999, the WGOH published the first review of previous year ocean climate conditions as an Annex of the WG official Report (Turrel, 1999), naming it *Annual ICES Ocean Climate Status Summary* (IAOCSS). A year later, the IAOCSS became a standalone document. In 2004 major formatting changes were introduced that helped homogenize the presentation (Hughes and Lavín, 2004), and key illustrations were included summarizing changes observed across the North Atlantic. In 2006 the IAOCSS was renamed *ICES Report on Ocean Climate* (IROC) (Hughes and Holliday, 2006). That report first incorporated the ISAS large-scale gridded fields produced by the LOPS laboratory and Coriolis operational oceanography center, a product which exploits the expansion of Argo autonomous profilers array (Gaillard et al., 2016).

In 2013 the WGOH implemented an interactive web version of the IROC[2] in collaboration with the ICES Data Center (**Figure 1**). Now the regional timeseries are updated as soon as observations are available during the year and the data can be freely downloaded. An archive of IROC reports is available on the website and summary highlights for current year conditions are posted immediately following the WG annual meeting. A recent improvement is the inclusion of newly developed indices, such as the Subpolar Gyre Index (Berx and Payne, 2017; Hátún and Chafik, 2018), which serves as a proxy for the strength and extent of the large scale circulation in the North Atlantic. Current efforts are focused on further standardization with regards to data processing (i.e., anomaly computation) and report layout (presentation of regional circulation maps, timeseries display, etc.).

WGOH analyses are based predominantly on existing repeated long-term *in-situ* hydrographic observations at stations and sections around the North Atlantic, the Nordic Seas and adjacent shelf seas, including the coastal, shelf and deep ocean. The idea behind the IROC is that regional experts perform analyses applying their specialized knowledge of a region to identify the most relevant available observational timeseries that support their assessment of hydrographic change. In this sense it is important to highlight that the IROC web is not a data repository but a heterogeneous collection of specialized timeseries. Most series are derived from CTDs deployed at fixed stations or along sections, with data extracted from either a single

[2]https://ocean.ices.dk/iroc/

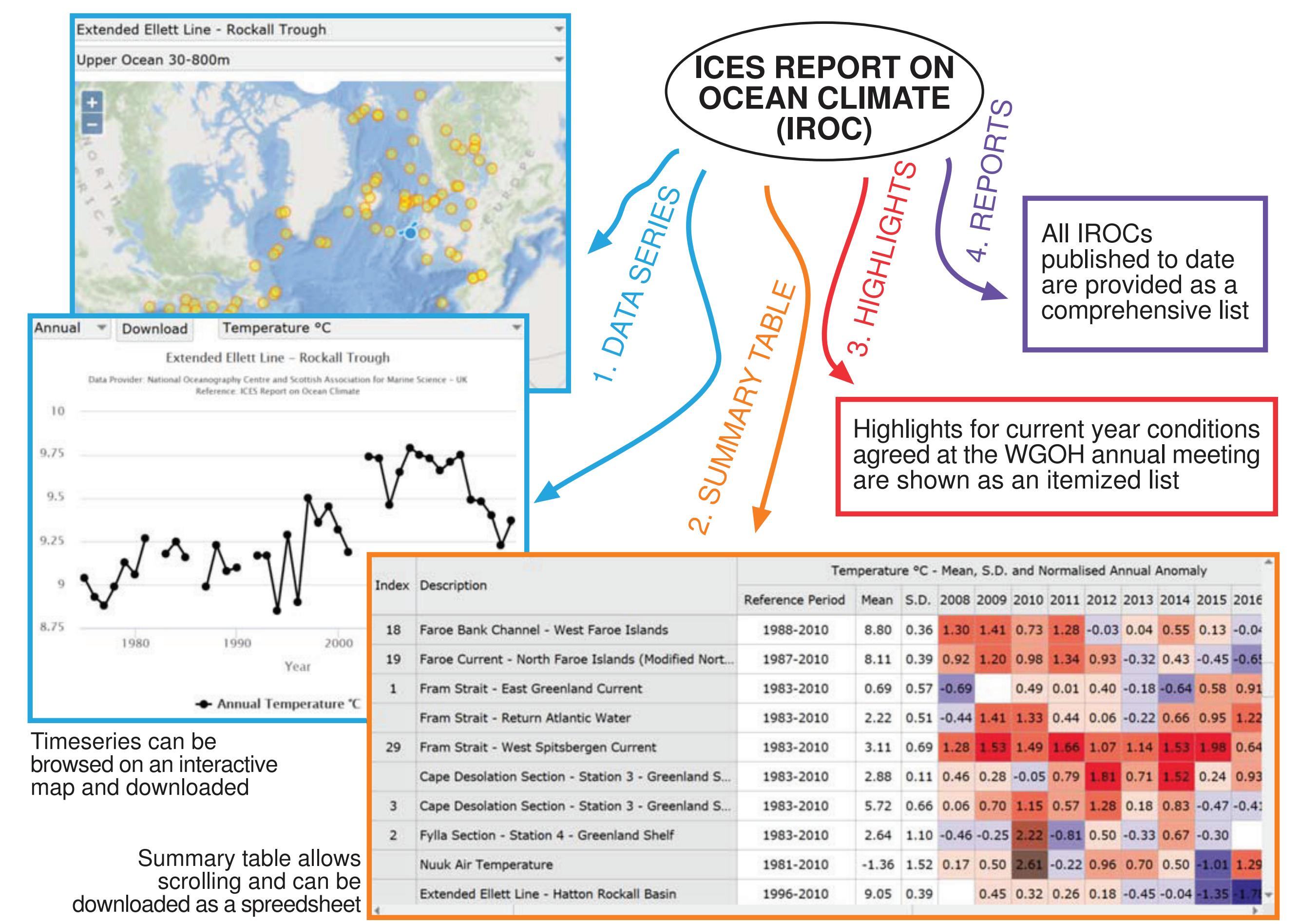

FIGURE 1 | Composite of content provided by the web version of the IROC report as of 2018. The portal is organized into four tabs containing data and elaborated information.

level or as vertical averages across a relevant water layer. Other series include long-term records of surface hydrography, sea-ice extent, atmospheric variables or other derived products such as heat content or estimated flows. Some of the timeseries reported in the IROC are the longest in the world and become more valuable to climate science with each passing year of continued measurement. These timeseries are not just long but also carefully analyzed by regional experts, thus of high quality to study and detect climate variability. **Figure 2** shows some statistics of the current timeseries used for the IROC as of its latest published issue (González-Pola et al., 2018).

3. THE WGOH AND THE GLOBAL OCEAN OBSERVING SYSTEM

The WGOH has served as a network to physical oceanographers in the North Atlantic for decades. While most science emerging from the observational systems that feed the IROC are performed independently by WGOH members within their science groups, collaborative studies have also emerged (e.g., Holliday et al., 2008; Holt et al., 2012; Hughes et al., 2012; Mork et al., 2014). Besides science, most outreach is achieved through the production of the IROC, currently used as a quick guide to environmental conditions for assessments and in support of other scientific studies (e.g., Nøttestad et al., 2015; Punzón et al., 2016; Widmer et al., 2016; Townhill et al., 2017; Brander, 2018). To continue the success of the IROC, the WGOH is continually seeking new ways to engage with a burgeoning global ocean observing community and to distinguish the IROC in an increasingly crowded field of ocean status reports. Generally speaking, internal concerns deal with the role of the WGOH in the future world of global ocean observations.

3.1. Ocean Status Reports, End-User Needs and the Science-to-Policy Pathway

The need for continuous monitoring, systematic analysis and quick release of data and derived products is the foundation of what is known as operational oceanography. The aim of the oceanographic community has long been to follow the lead of the more advanced meteorological services, expecting that monitoring programs are coordinated and oceanographic data

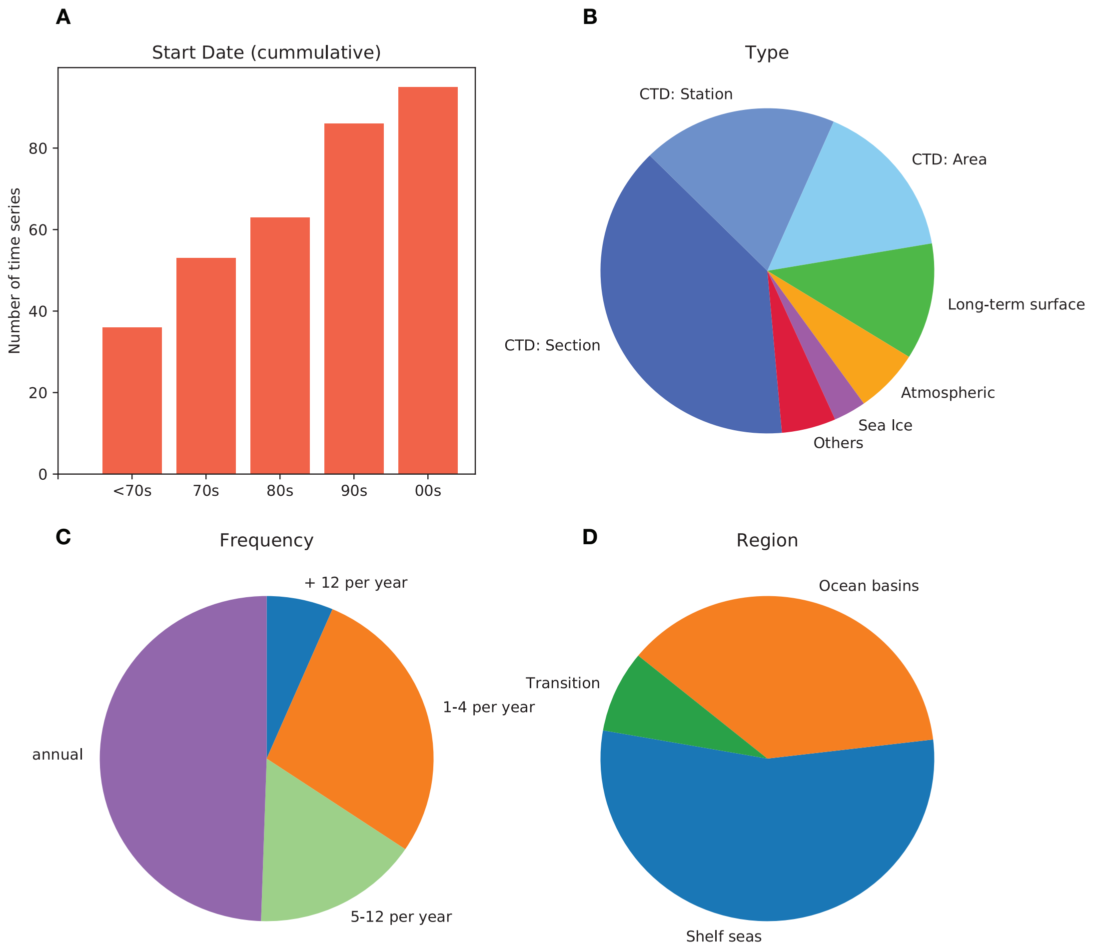

FIGURE 2 | Basic properties of timeseries included in the IROC. The report currently includes 95 timeseries from 76 locations, provided by 32 organizations across 15 countries. **(A)** Histogram of the starting dates of the timeseries grouped by decade (cummulative), **(B)** timeseries type: where "others" accounts for modeled flow, heat content anomaly, fresh water anomaly and spatial extent of specific water masses (i.e., the Cold Intermediate Level), **(C)** timeseries sampling frequency, **(D)** oceanic region, where 'Transition' includes stations over continental slopes and within straits.

are gathered systematically using standardized procedures and are freely distributed as soon as possible. The GOOS program has managed to gather the efforts of several institutions/consortia in this direction.

Along with increasing data availability, gridded products and reanalysis have been used as a means of objectively synthesizing information, which can then be described in science-based reports that aim to provide easy-to-understand summaries to end users. The Intergovernmental Panel on Climate Change (IPCC) has been publishing global assessment reports every 5–8 years since 1990 (IPCC, 1990). Similarly, the National Oceanic and Atmospheric Administration (NOAA) has been publishing an annual State of the Climate report as a standalone peer-reviewed publication since 1996 (Halpert and Bell, 1997). Since 1994, the World Meteorological Organization (WMO) has published their annual Statement on the Global Climate (WMO, 1994). Over time, these three international flagship reports have introduced specific sections dedicated to the recent evolution of ocean climate, focusing on the ocean heat content, salinity, ocean circulation and more recently considering biogeochemistry. Current issues (IPCC, 2013; Hartfield et al., 2018; WMO, 2018) provide a high degree of detail in their ocean chapters. Region-specific ocean climate state reports are also being produced individually by countries either regularly or without predefined sequence.

In parallel to international efforts and those of individual countries, the European Union has developed Copernicus[3] as a joint Earth Observation and Monitoring program built upon the *in-situ* observational capabilities of member states and satellite developments by the European Space Agency. Copernicus provides environmental services to the scientific community, policy-makers and general users. The Copernicus Marine Service has since 2016 released the Ocean State Report (von Schuckmann et al., 2018), dealing both with the Global Ocean and regional European Seas. Independent of Copernicus, the European Union

[3]www.copernicus.eu

has set the Marine Strategy Framework Directive[4] (MSFD) as a legal framework to protect the marine environment from anthropogenic pressures across European waters. Contrary to large initiatives within GOOS in which sampling relies on voluntary efforts by institutions and countries, the MSFD enforces the establishment of (i) monitoring programs, (ii) objective environmental targets and (iii) a program of measures designed to achieve or maintain an objectively defined "Good Environmental Status". Ocean Climate conditions are considered by the MSFD as an indirect anthropogenic pressure on the ocean environment, hence the monitoring of large-scale hydrographic conditions is a background prerequisite required for the MSFD as a whole. Interpretations on whether the MSFD enforces the development of specific large-scale monitoring programs for the background basic ocean variables have been varied (González et al., 2016).

As indicated, this profusion of ocean climate reporting raises concern about the current degree of complementarity and/or redundancy. Accordingly, the WGOH is concerned that the IROC remains relevant, distinguished in purpose and value to its users. The essential question, common to any report-producing team, is whether it is useful to end-users and if so how it should evolve to become more useful. Success requires a solid understanding of user needs. Sitting within the ICES, a body organized to encourage interdisciplinary networking, the WGOH-IROC is in a unique position to provide information and advice that is timely and relevant to the management of living marine resources. Oceanographic conditions are fundamental to understanding and predicting species distribution, forecasting recruitment, improving ecological models, etc. but marine ecology/fisheries scientists find it difficult to distinguish between available environmental products and effectively apply them to their work (ICES, 2018). The WGOH delivers expertise through the IROC and member engagement, which is becoming increasingly important as focus continues to shift toward ecosystem-based approaches for the management of marine resources (Dickey-Collas, 2014).

Several WGOH members are closely engaged with fisheries and environmental management activities, participating in multidisciplinary assessments and studies. In our experience, collaborators typically seek a succinct summary of the regional oceanography that can be used to frame a particular study, or a representative index of ocean variability that can be correlated with other measures of ecological change. In this sense, a simple representative timeseries or a few summarizing highlights are often sufficient. Hence, we expect the standard IROC user to focus on a specific region, while keeping in mind the general broader ocean context. A major strength of the IROC lies in the detailed regional analyses contributed by local experts from data products specifically tailored to the regional oceanography. Future developments of the IROC should not overlook this strength. Direct contact with potential users indicates that further developments may include a regional interpretation of available operational products and assessment of ocean state forecasts.

Along with improvements to the IROC, it is critical to develop a strategy for promoting its use, aimed at demonstrating the relevance of the report in future observing programs and its value for end-users. The current approach uses the ICES outreach strategy coordinated by a communications and publications department. IROC report highlights are published on the ICES news web page[5] before publication of the full report, and extensive social network activity is triggered along the process. A major target in the WGOH is having the report ready in summer to facilitate its use at the ICES Annual Science Conference. In parallel to ICES efforts, WGOH members use their own science networks and conference attendances to promote the IROC. Future success of the IROC will be tracked through its bibliometric performance, with the recent introduction of digital identifiers (doi) in Cooperative Research Reports.

ICES' goal of providing unbiased science-based advice to competent authorities requires full involvement of all EGs in the science-to policy pathway. The transfer of scientific advances into practical management tools builds upon the underlying idea that permanent two-way communication and strong coordination are pivotal. Current ICES structure relies on two main pillars, the Science and the Advisory Committees, who jointly struggle to facilitate such coordination[6]. WGOH-IROC forms a critical bridge between data collected by independent scientists/institutions/countries for research and environmental monitoring, and actual policy advice.

3.2. IROC Timeseries and GOOS

As seen in section 2, the WGOH analyses reported in the IROC are mostly based on the existence of long-term high-quality repeat hydrographic timeseries, primarily derived from *in-situ* sampling. These timeseries are considered representative at regional scale, providing notable coverage of the shelf seas and ocean boundaries. Traditional *in-situ* sampling was the only option for most of the twentieth century but the last two decades have yielded outstanding advances in routine automated sampling of the ocean in terms of oceanographic fixed buoys (WMO-IOC, 2018), the Argo array (Riser et al., 2016) and more recently regular glider missions (Rudnick, 2016).

The introduction of new technology will allow for the continuation of several long-established timeseries in the North Atlantic. A relevant case is the Ellett Line (Holliday and Cunningham, 2013), that started in 1975 and has been covered by an annual cruise until now. Beginning in 2018 this regular cruise will be superseded by a new observation system (OSNAP[7]) utilizing moored arrays, glider missions and biannual shipboard sampling. The representative regional IROC timeseries will be continued using these data supplemented by observations from the Argo array. In another example, high-frequency subsurface

[4]http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive

[5]www.ices.dk/news-and-events/news-archive/news/Pages/Ocean-climate-highlights.aspx

[6]www.ices.dk/community/groups/Pages/wkscience2advice.aspx—Workshop on translating science into advice. 2018.

[7]The Overturning in the Subpolar North Atlantic Program www.o-snap.org

sampling by the Norwegian Ocean Weather Station "M" was discontinued with the removal of the last weather ship in 2010 (Yelland et al., 2009). As a replacement, hydrographic observations from this location derive now from subsurface instrumentation in the framework of OceanSITES[8] plus research ships visits up to five-six times per year. Finally, surface temperature measurements collected via ship of opportunity at 52°N along the southern North Sea were discontinued in 2002 with the removal of the ferry line. However, the timeseries may now continue using observations from a nearby Smartbuoy (See Figure 77, p.81, in González-Pola et al., 2018).

Currently, only a portion of the IROC timeseries are systematically being incorporated into Global Operational Databases and hence contributing effectively to GOOS. This issue is a major concern of the WGOH, already highlighted in the previous white paper authored by the group (Holliday et al., 2010). One challenge is that most hydrography derived from national monitoring programs are only available in delayed mode, while current demands expect real-time availability. In addition, many repeat hydrography programs do not meet the GO-SHIP[9] sampling criteria and hence datasets are not incorporated through JCOMMOPS[10]. The lack of a home for classical hydrographic cruises has been highlighted as a weakness of the current JCOMMOPS structure. On the other hand, the ICES Data Center has long focused on hosting delayed mode CTD and discrete water bottle data from ICES areas, which are routinely incorporated into the US World Ocean Database and Atlas[11] and made available to the global community.

As automated sampling develops, science programs are beginning to consider the relative benefits of more traditional *in-situ* sampling. Oceanographic cruises are becoming more multidisciplinary, with biogeochemistry often included as a mandatory component, while hydrography stands as a basic record. Further, *in-situ* hydrography remains essential for the groundtruthing of data from autonomous vehicles and profiling floats. Hence, while autonomous systems may supplement *in-situ* measurements made via ship or moored array in long-standing programs, we argue that these traditional observations will be required well into the future. Despite the delayed delivery, IROC timeseries offer significant added value to GOOS programs. In particular, (i) IROC observations sample the deep ocean in a variety of locations across the North Atlantic, filling a major gap in present day GOOS where deep observations (> 2000 m) are limited to GO-SHIP sections (Deep Argo floats and deep gliders still have a long way to fully cover the gap) and (ii) IROC observations bridge a gap between the blue ocean and regional seas, shelves and oceanic boundaries, where most classical monitoring programs take place but the Argo network cannot access.

[8]www.oceansites.org
[9]The Global Ocean Ship-Based Hydrographic Investigations Program www.go-ship.org/DatReq.html
[10]WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology *in-situ* Observing Programmes Support Centre www.jcommops.org
[11]www.nodc.noaa.gov/about/oceanclimate.html

4. CONCLUSION AND OUTLOOK

For decades, the ICES-WGOH has provided ICES and the oceanographic community with information on the condition of the North Atlantic Ocean by updating and reviewing results from standard long-standing hydrographic sections and stations. WGOH continues a long tradition of international collaboration, bringing together physical oceanographers with regional expertise and a rich collection of ocean data to contribute to this annual assessment. While global ocean observation has evolved in the past decade, greatly increasing in volume and complexity, the WGOH-IROC continues to be a key link between regional ocean monitoring and research, and actual policy advice. Looking toward the future, ICES-WGOH has much to offer the burgeoning GOOS community, including a history of observations in key areas of the ocean and experience in meeting the needs of fisheries scientists. However, further engagement with GOOS is essential. WGOH will continue to track key observational timeseries, stressing continuity and quality while working to incorporate these data into the GOOS system.

DATA AVAILABILITY

The datasets analyzed for the IROC discussed in this white paper can be downloaded at the IROC online web page https://ocean.ices.dk/iroc/

AUTHOR CONTRIBUTIONS

CG-P conceived the white paper and coordinated the group. CG-P, PF, KL, and NH designed the paper structure and defined the key contents. CG-P took the lead in writing the manuscript and PF performed thorough draft reviews. RG analyzed the characteristics of the collection of timeseries and created a graphical representation of the outcome. All authors commented on the manuscript providing specific feedback.

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Developing an Integrated Ocean Observing System for New Zealand

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New Zealand (NZ) is an island nation with stewardship of an ocean twenty times larger than its land area. While the challenges facing NZ's ocean are similar to other maritime countries, no coherent national plan exists that meets the needs of scientists, stakeholders or kaitiakitanga (guardianship) of NZ's ocean in a changing climate. The NZ marine science community used the OceanObs'19 white paper to establish a framework and implementation plan for a collaborative NZ ocean observing system (NZ-OOS). Co-production of ocean knowledge with Māori will be embedded in this national strategy for growing a sustainable, blue economy for NZ. The strengths of an observing system for a relatively small nation come from direct connections between the science impetus through to users and stakeholders of an NZ-OOS. The community will leverage off existing ocean observations to optimize effort and resources in a system that has historically made limited investment in ocean observing. The goal of the community paper will be achieved by bringing together oceanographers, data scientists and marine stakeholders to develop an NZ-OOS that provides best knowledge and tools to the sectors of society that use or are influenced by the ocean.

Keywords: ocean observation network, ocean modeling, marine community, Mātauranga Māori, changing ocean climate

INTRODUCTION

New Zealand (NZ) is an island nation with stewardship of an ocean area twenty times its landsize, yet it does not currently have an ocean observing system (OOS). NZ's marine space spans the subtropics to the subantarctics with islands to the north, south and east far beyond its two main islands (**Figure 1**). The shelf sea environment includes broad plateaus, narrow steep shelves and wide continental shelves incised with submarine canyons. Warm, saline subtropical water (STW) arrives in NZ from the north via the South Pacific Gyre and East Auckland Current (EAUC). From the south, subantarctic water (SAW) with lower salinity and temperature flow near NZ in the Southland Current adjacent to the South Island and in the northernmost branches of the Antarctic Circumpolar Current (Chiswell et al., 2015). Dynamic processes in the shelf seas include strong tidal flows in Central NZ, large internal tides and significant terrestrial inputs of freshwater, sediment and carbon after storms (Zeldis and Swaney, 2018; Stevens et al., 2019).

In dollar terms, NZ's marine economy is estimated to be worth around $NZ four billion (Ministry for the Environment [MfE], 2016). NZ's exclusive economic zone (EEZ) underpins an emerging blue economy; it is globally recognized to support high biodiversity of seabirds and marine mammals, a productive fisheries sector and a growing aquaculture industry. Stewardship of this large area's resources and values requires robust scientific knowledge and understanding to ensure sustainable management of marine ecosystems, which are influenced by multiple stressors and a changing climate.

Indigenous perspectives are a key aspect of NZ's policy and science landscape and are particularly relevant in developing effective ocean stewardship that is informed by an NZ-OOS. The government's Vision Mātauranga (VM) policy was developed to unlock the potential of Mātauranga Māori, which is broadly defined as Māori or traditional knowledge, comprehension or understanding of the universe (Ministry of Research Science and Technology [MoRST], 2007). Guardianship or kaitiakitanga of Aotearoa's (te reo Māori for NZ) land and sea is an intrinsic concept in Māori science. Joint efforts between Mātauranga Māori and western science practices are becoming more common providing a holistic, inclusive, system-wide knowledge of the natural world.

The Why and Why Now

New Zealand faces similar challenges – managing multiple stressors, climate change, sea-level rise, ocean acidification, and impacts from changing terrestrial fluxes – as other maritime countries. A sense of urgency exists to understand, predict and mitigate, at a national scale, the ocean and ecosystem responses to these global problems (Stevens and O'Callaghan, 2015). **Figure 2** outlines high-level themes of interest for users and beneficiaries of an NZ-OOS and its integrated data products. Underlying these themes are six key issues identified by the NZ community as kaitiakitanga priorities.

1. Land-sea connectivity and associated stressors (e.g., sedimentation, contaminants).
2. Coastal and bluewater carbon budgets.
3. Sustainable extraction of marine resources (e.g., seabed mining, tidal energy).
4. Sustainable seafood sector including both wild caught fisheries and aquaculture.
5. Multi-scale drivers and response of the ocean state.
6. Maritime safety and transport optimization.

The concept of an OOS is not new to NZ; factors relating to national priorities and NZ's policy and science systems, combined with limited resources have inhibited the development of an NZ-OOS. Resources commensurate with a population of $\sim$5 million people and a dominant agricultural sector for many years underpinned a landward focus (Hendy and Callaghan, 2013). Long term coastal warming (Shears and Bowen, 2017) and recent variability in fish stocks and impacts on aquaculture along with extremes in ocean temperature have prompted an urgent rethink of how marine sectors will respond to changing environmental drivers (Salinger et al., 2019).

The NZ Science System

The NZ science system is small, which can be both advantageous and limiting in terms of developing and implementing an OOS. The OECD Research & Development (R&D) survey identified R&D as a percentage of GDP as 1.263 and researchers per thousand employment (FTE) as 7.94 (OECD, 2018). The R&D expenditure proportion is around half the OECD average. Several significant changes have taken place in the NZ science system sector over the last three decades. In 1991 Crown Research Institutes (CRIs) were formed, essentially restructuring the Government science sector from a single research provider (the Department of Scientific and Industrial Research, DSIR) into several institutes that were built around a hybrid business and public-good model.

Marine scientist capacity is modest across NZ. Major employers in the sector are the National Institute of Water and Atmospheric Research (NIWA, a CRI), four (out of seven) universities, Meteorological Service of New Zealand (MetService), MetOcean Solutions and the Cawthron Institute (independent research organization). Research foci of the national institutes has evolved over the past 25 years from public-good science to stakeholder "co-production." Current hallmarks of the funding landscape include (1) separation between climate science and ecosystem research, (2) under-valuing of sustained monitoring of the ocean and (3) inability to support long term (greater than 5 years) projects. Funding for the development and implementation of an NZ-OOS will require a combination of long-term government investment, organizational co-investment and private sector contributions.

NZ-OOS Planning Workshop

A successful workshop with multi-institutional support was held in August 2018. Participant organizations were NIWA, Cawthron, MetService, Centre for Space Science Technology (CSST), Ministry for Primary Industries (MPI), Ministry for the Environment (MfE), Department of Conservation (DOC), NZ Navy, Defence Technology Agency (DTA), Auckland and Otago Universities, and the Coastal Special Interest Group (C-SIG) that represents the national network of regional councils with jurisdiction out to 12 nautical miles. NIWA's Pou Hononga for Māori and the Marine Environment provided a Mātauranga Māori contribution. Outcomes from workshop discussions form the basis of this white paper.

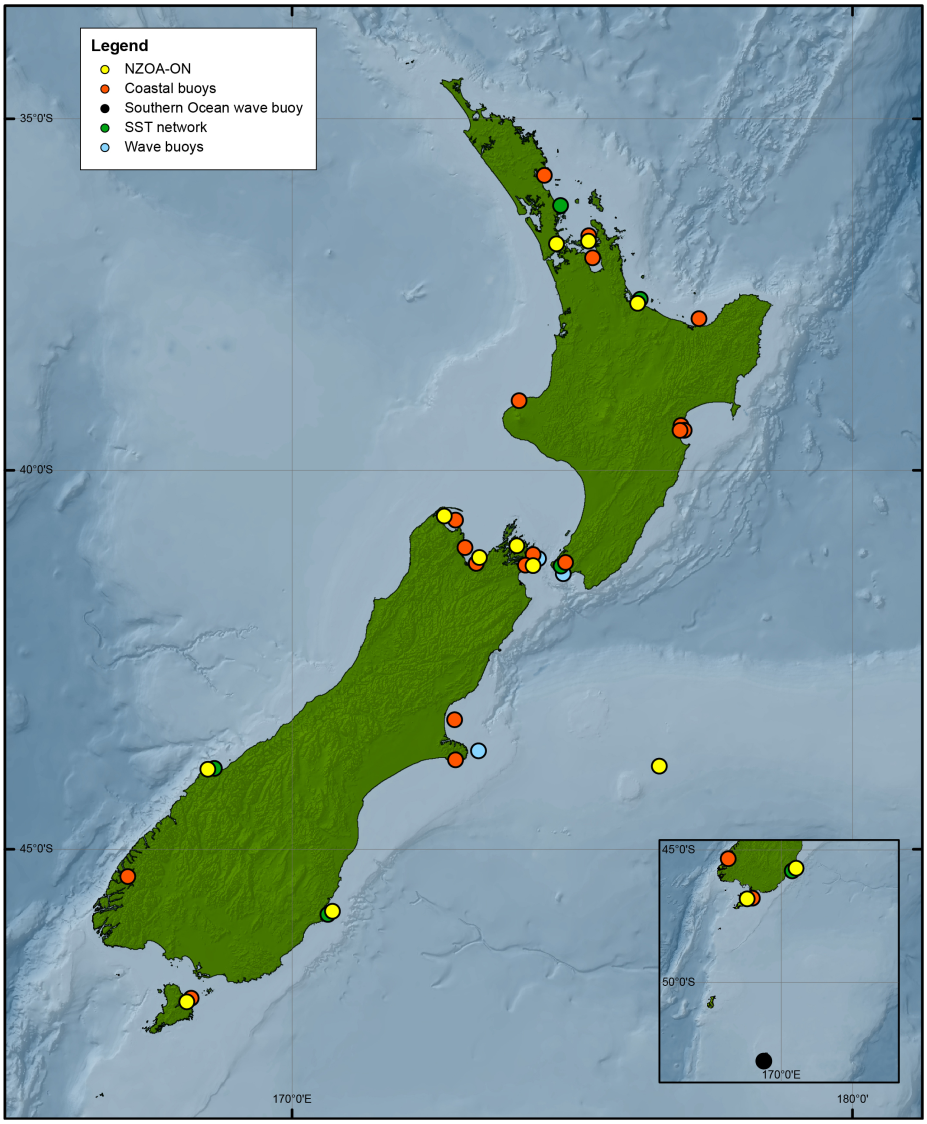

FIGURE 1 | Map of New Zealand (NZ) with observational assets are overlaid on the bathymetry. Assets shown are wave buoys (blue dots), coastal buoys (orange dots), NZOA-ON (yellow dots), SST network (green dots) and the Southern Ocean wave buoy (black dot).

OCEAN OBSERVATIONS

Present State of NZ Observations

The two longest sea surface temperature (SST) monitoring sites are from opposite ends of Aotearoa, with the Portobello station (University of Otago) started in 1953, followed by Leigh (University of Auckland) in 1967. Growth and reduction of a coastal SST monitoring network has occurred over intervening years (Greig et al., 1988) and as of writing there are five coastal SST stations (**Figure 1**). Other long term observations are the sea level network around NZ[1], which has also had to rationalizatise the number of sites in recent years. Two biophysical moorings were located at 41°S, 178°30′E and 46°40′S, 178°30′E in STW and SAW for 10 years from 2002 to 2012 to resolve oceanic carbon budgets (Nodder et al., 2016).

University of Otago and NIWA established the NZ Ocean Acidification observing network (NZOA-ON) with 14 sites around NZ, linked to the Global Ocean Acidification Observing Network (GOA-ON). The NZOA–ON expands on the successful *Munida* transect off the coast of the South Island established in 1998 that is the southern hemisphere's longest-running record of pH (Bates et al., 2014) and surface variability across STW and SAW (Currie et al., 2011).

There are few wave and coastal moorings considering the length (15,000 km) and variability of NZ's coastline. The Firth of Thames mooring is the longest at 20 +years (1998 to now, Zeldis and Swaney, 2018). Sampling durations are typically shorter (<10 years), generally deployed by regional councils

[1]https://www.niwa.co.nz/our-services/online-services/sea-levels

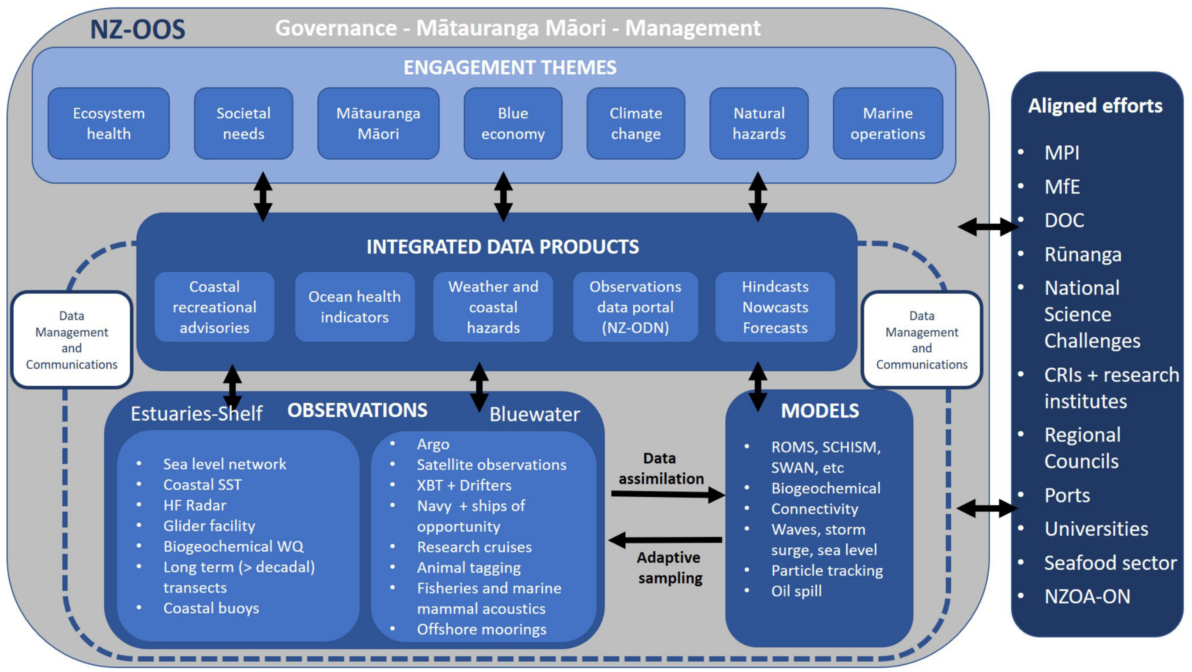

FIGURE 2 | Framework for the NZ-OOS building on existing efforts in NZ. The proposed structure illustrated has been adapted from that used for the Southeast Coastal Ocean Observing Regional Association.

in conjunction with Cawthron or NIWA and tend to have a focus on surface coastal water quality issues and sedimentation (**Figure 1**). Passive acoustics moorings to characterize marine mammal migratory pathways have also been deployed for 12 months in Central NZ. Recently, ocean gliders have been used to observe NZ shelf seas processes with 20 missions since 2015 (O'Callaghan, pers comm).

Bluewater observations have historically been dominated by mooring deployments of less than 2 year duration and voyage-based hydrographic surveys to characterize boundary currents around NZ. For example, Tasman Sea boundary experiments (Stanton and Moore, 1992), and variability studies of the East Auckland Current (EAUC) (e.g. Stanton et al., 1997; Fernandez et al., 2018, and many others), Norfolk Ridge (Sutton and Bowen, 2014) and, Southland Current (Sutton, 2003).

New Zealand has been an important part of the Global Argo program since the early 2000s with NIWA's vessel R/V Kaha Ora deploying 1287 floats in the Pacific, Indian and Southern Oceans. NIWA's RV Tangaroa has deployed a further 147 floats. The most southerly wave buoy in the world has been maintained by the MetService since 2016 at 52.7°S. EXpendable Bathy Thermographs (XBTs) have been deployed along two tracks ending in NZ roughly four times per year (Sutton et al., 2005). XBTs are also routinely deployed by the NZ Navy.

Plans for a Future Observational Network

Building on the framework of existing observations, a series of workshops will be held with scientists and key stakeholders in regulatory agencies, CRIs and universities. These workshops will define the mix of what infrastructure is most likely to address the key research themes in an ambitious and affordable way for the next 1, 5 and 10 years. With international experience to draw on, we are well placed to implement an NZ-OOS in a cost-effective manner to achieve meaningful and sustained observational coverage with potential to grow strategically in the future.

We propose a number of sentinel sites (analogous to the National Reference stations in the Australian IMOS context) that are physically occupied at adequate frequency for biogeochemical and physical water sampling of essential ocean variables (EOVs). Sentinel sites will be instrumented appropriately to develop environmental baselines in a changing climate. In addition, we will identify a backbone network of high frequency (HF) radar and glider deployments to provide boundary current data, and context for model data assimilation.

A creative approach will be required to get meaningful coverage across NZ's large EEZ. It is recognized that the NZ seafood sector provides an opportunistic pathway for data collection and effort is already being made with this sector. The NZ Navy has plans to facilitate oceanographic data collection. By using vessels of opportunity, we can optimize data coverage while minimizing costs to NZ-OOS.

OCEAN MODELING

Present Status

Physical and biogeochemical ocean modeling is undertaken by a number of organizations with each team having their preferred model (ROMS, Schism/SELFE, SWASH, SWAN, WW3, Gerris, and Basilisk), domain (coastal to global scale), grid (structured, unstructured, curvilinear or adaptive), timeframe (days, weeks to years) and parameters (physics, biogeochemistry, sediment transport, waves). Typically these models have been developed either for specific process studies (e.g., Hadfield et al., 2007), or in response to stakeholder requirements and resource consent applications. Operational forecasts of waves, storm surge and barotropic circulation exist at the national scale.

An OOS is acknowledged as incomplete without a nationally coordinated ocean modeling program. The benefits are 2-fold: observational design is optimized from model simulations while modeling efforts are constrained by relevant observations. The Australian Integrated Marine Observing system (IMOS) program did not initially include funding for ocean modeling. Australian Coastal and Oceans Modeling and Observations (ACOMO) was born 5 years after IMOS and provides a valuable national perspective on modeling and observational networks. It is considered prudent to incorporate an integrated modeling system in NZ-OOS from the outset.

Plans for Ocean Modeling and Data Assimilation

Close connections between the NZ science community and stakeholders means that knowledge relevant to industry is paramount. A national modeling framework that assimilates new and historic observations is essential for an integrated NZ-OOS. In this way the observations and modeling initiatives are intimately coupled. A high resolution coastal ocean reanalysis (ocean state estimate) is being developed by MetOcean Solutions[2]. This modeling system will include a 25-year data assimilating physical model and will provide open access daily coastal ocean forecasts in the next 1 to 3 years. Model hindcasts of physics and biogeochemistry are being developed by NIWA at the EEZ scale. Observation impact experiments (Kerry et al., 2018) and observing system simulation experiments (Kourafalou et al., 2015) provide both context for ongoing model development and the evolution of the observing system.

DATA, TOOLS, AND DELIVERY

Open Data and Legacy Data Issues

Open access to data underpins OOS frameworks globally and success of the proposed NZ-OOS will be intertwined with availability of data, data uptake and publications. The necessary shift in perspective is underway in NZ but is happening against a backdrop of a better understanding of what open data means and resourcing open data. The proprietary nature of data from commercial projects is questionable, particularly if they were collected with resources and capacity co-supported by government funding.

Open data is universally recognized as a "good thing" (Schmidt et al., 2016), however, there remain issues relating to quality assurance and usage restrictions. Stronger mandates from the funding agencies will strengthen the requirements for data sharing. New Zealand Government Open Access and Licensing [NZGOAL], 2019 provides a framework for open data to apply to all sector data.

In 2017 the New Zealand Ocean Data Network (NZODN)[3] was launched, modeled on the Australian Open Data Network (AODN). It is now a collaboration between NIWA and Land Information New Zealand (LINZ). The AODN Portal provides access to all available Australian marine and climate science data and provides the primary access to IMOS data. A key point of difference is that IMOS is national collaborative research infrastructure, supported by Australian Government – no equivalent exists yet in the New Zealand system, although this is our aspiration. The NZODN and AODN are regional reflections of a growing international trend for open data resources.

Data Science Products and Tools

The evolution of useful data products becomes iterative as users tend to be resourceful and can use data in ways not obvious in the initial planning. This *ad hoc* co-production can be enhanced through better and wider end-user input to the design phase. The impact of the NZ-OOS will be enhanced if it provides easy pathways for uptake, manipulations and re-dissemination from the outset. Stakeholders are likely users of tools and while uptake may be slow they will provide robust interrogation of the results whereas the public are likely to be fast and idiosyncratic in their usage. Both pathways provide connections between science product and government policy.

Mātauranga Māori

It is possible that NZ can be among the world leaders in the integration of traditional knowledge with western science into an NZ-OOS. Mātauranga-a-iwi is being advanced through Treaty settlements legislation and other negotiated agreements, which is creating co-management arrangements and increased participation by Māori in all areas of ocean research, policy and management. Māori are seeking Mātauranga and science advice to address aspirations in halting ocean degradation through adaptive management strategies, inclusive of both traditional and contemporary forms of kaitiakitanga. There is potential for non-sacred traditional knowledge to be shared through knowledge platforms such as Māori environmental forums and Rûnanga (a recognized iwi or tribal authority) therefore enhancing uptake and integration.

TOWARD AN INTEGRATED NZ-OOS

The NZ-OOS is a bottom-up community-driven initiative and its success depends on a joint, inclusive approach. Overcoming longstanding limitations established by the hybrid science model over nearly 30 years will require ongoing and meaningful cross-institutional engagement. With collaborative governance, broad participation, and sustainable central government funding, NZ is fully capable of implementing a world-leading OOS that

[2]https://www.moanaproject.org/

[3]https://nzodn.nz/

provides effective kaitiakitanga of its vast EEZ in a changing climate. This white paper is the first step in the implementation process. **Figure 2** provides the framework for the proposed NZ-OOS from governance through to details of data collection platforms. Ecosystem-based management tools that are being developed in National Science Challenges (aligned efforts) will allow integration of monitoring components at the 10-year time scale.

Without doubt the biggest hurdle to overcome is sufficient and sustained resourcing of the proposed NZ-OOS. Often the limiting factor in the development of a highly sophisticated ocean observing system such as the one detailed here is the available funding mechanisms. Observational data streams obtained via existing research programs from central government funding will be the backbone of NZ-OOS in the short- to medium term. Resources to support working group progress will come from individual organizations. Long-term funding was identified by the community as much more difficult to secure. Ultimately, this will require a business case to be submitted to the NZ government to fund future ocean infrastructure.

By the end of the first year, we aim to develop a draft strategic plan built on a well-designed framework and collaborative governance structure. With a sound plan in place, a business case for funding an NZ-OOS will be developed. Many of the elements, both observational and modeling, already exist in NZ. It is encouraging that the NZ-OOS framework has begun to provide, since the August 2018 workshop, a mechanism for new connections of aligned efforts from organizations (**Figure 2**).

To achieve the year 1 objective, we will establish:

1. A pan-NZ steering committee and governance board.
2. Four working groups focused on estuaries to shelf, bluewater, data systems, and communications. The scope of each group will be expansive to overcome organization and science discipline silos.
3. A catalog of observational assets and existing marine data for NZ (**Figure 1**).
4. A strategy for implementing Mātauranga Māori in an NZ-OOS.

After 5 years, the NZ-OOS could include:

1. A widely subscribed data system built around the NZ-Ocean Data Network (NZ-ODN) providing data to a wide range of users.
2. A network of coastal monitoring assets in key regions across a range of organizations that follow standardized data exchange protocols.
3. Access to model hindcast and reanalysis products for simulating and visualizing NZ's EEZ.
4. The ability for rapid response for forecasting coastal hazards, oil spill trajectories, and biosecurity risk.
5. Implementation of a network of sentinel sites for observing EOVs along latitudinal and anthropogenic gradients.
6. Develop and implement sentinel fish and marine megafauna data collection programs that indicate ecosystem change.

After ten years, the NZ-OOS could include:

1. A widely accessible OOS visualization system that enables society to engage with ocean data in new and exciting ways.
2. Data assimilating operational models providing near-real time forecasting of our entire EEZ.
3. Commitment from the seafood industry, with the entire fishing fleet and aquaculture farms established as observing platforms.
4. Integration of ecological layers and the inclusion of, biogeochemical and molecular ocean data through aligned sampling programs.
5. Successful integration of Mātauranga Māori into a national OOS framework.

To summarize, with the integration of Mātauranga Māori, NZ's science, technologies and closely connected community provides a timely opportunity to develop an exemplary NZ-OOS that will provide a world-leading example of ocean stewardship, and enable ocean knowledge, data and tools to be openly accessed for the benefit of NZ's economy, social well-being and ocean health.

AUTHOR CONTRIBUTIONS

JO led the writing and NZ-OOS workshop. CS, MR, and CC contributed to respective sections of the manuscript. All other authors either participated in the August workshop or provided feedback on various versions of the manuscript.

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frontiers in Marine Science

REVIEW
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Better Regional Ocean Observing Through Cross-National Cooperation: A Case Study From the Northeast Pacific

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The ocean knows no political borders. Ocean processes, like summertime wind-driven upwelling, stretch thousands of kilometers along the Northeast Pacific (NEP) coast. This upwelling drives marine ecosystem productivity and is modulated by weather systems and seasonal to interdecadal ocean-atmosphere variability. Major ocean currents in the NEP transport water properties such as heat, fresh water, nutrients, dissolved oxygen, pCO_2, and pH close to the shore. The eastward North Pacific Current bifurcates offshore in the NEP, delivering open-ocean signals south into the California Current and north into the Gulf of Alaska. There is a large and growing number of NEP ocean observing elements operated by government agencies, Native American Tribes, First Nations groups, not-for-profit organizations, and private entities. Observing elements include moored and mobile platforms, shipboard repeat cruises, as well as land-based and estuarine stations. A wide range of multidisciplinary ocean sensors are deployed to track, for example, upwelling, downwelling, ocean productivity, harmful algal blooms, ocean acidification and hypoxia, seismic activity and tsunami wave propagation. Data delivery to shore and observatory controls are done through satellite and cell phone communication, and via seafloor cables. Remote sensing from satellites and land-based coastal radar provide broader spatial coverage, while numerical circulation and biogeochemical modeling complement ocean observing efforts. Models span from the deep ocean into the inland Salish Sea and estuaries. NEP ocean observing systems are used to understand regional processes and, together with numerical models, provide ocean forecasts. By sharing data, experiences and lessons learned, the regional ocean observatory is better than the sum of its parts.

Keywords: ocean observation, marine eco system, coastal oceanography, ocean model and observations comparison, data delivery

INTRODUCTION

An array of ocean observing assets, as well as numerical ocean circulation and biogeochemical models, focus on the Northeast Pacific (NEP) off the coasts of Oregon, Washington, British Columbia, and Alaska. This region includes the open-ocean bifurcation of the North Pacific Current (aka West Wind Drift) into the southward flowing California Current and the northward flowing Alaska Current. Spring and summer wind-driven coastal upwelling strongly influences waters on the continental shelf and slope off of the Pacific Northwest (PNW) coast (Smith, 1974; Thomson, 1981). In the winter, the PNW coastal waters are subject to strong wind-driven downwelling, considerable freshwater and iron input from rivers (Chase et al., 2007), large waves and swift northward currents (Mazzini et al., 2014). Both the Fraser and Columbia Rivers, the largest sources of freshwater to the North American west coast, also influence the region, as do numerous distributed coastal river systems. Highly productive marine fisheries and aquaculture facilities are found in PNW waters, including a diverse range of valuable and iconic species like Dungeness crab, razor clams, oysters, salmon, halibut, and hake. The NEP is home to the Cascadia Subduction Zone where the Juan de Fuca Plate dives beneath the North American Plate. The region is subject to seismic activity, most consequentially by large (magnitude > 8) subduction zone earthquakes with inter-event times ranging from 200 years to 1,200 years (Atwater, 1987). The PNW is home to several major metropolitan areas with a population of about 10 million people and NEP waters include key shipping routes. Observations and models cover the full-ocean depth and seafloor beneath, spanning from the continental shelf and slope to the open ocean, including major estuaries and inland seas, and reaching all the way to shore (**Figure 1**).

Waters off the PNW are influenced by climate and ocean anomalies on a year-to-year ("interannual") and decade-to-decade ("interdecadal") timescale (**Figure 2**). In response to interannual variability forced by the El Niño Southern Oscillation at the equator, upper-ocean stratification, ocean currents, and local winds change in the NEP through signals that arrive through both the ocean and atmosphere (Huyer et al., 2002). A relatively higher sea level and warmer water is present during El Niños and vice versa for La Niñas. There is evidence for larger river discharge into the ocean following La Niña events (Dracup and Kahya, 1994), notably in 2011 (Mazzini et al., 2015). During the winter of 2013–2014, the atmospheric Jet Stream shifted anomalously northward leading to less wind-driven mixing in the central Gulf of Alaska, that subsequently led to the formation of a large region of anomalously warm surface water. This "warm blob" (Bond et al., 2015) was subsequently observed to be advected south and toward the Canadian and United States west coasts, persisting on the shelf at least through 2017 (Barth et al., 2018) and until 2018 at 140 m in a deep British Columbia fjord (Jackson et al., 2018) (**Figure 2**). On interdecadal time scales, PNW waters are affected by the Pacific Decadal Oscillation that manifests itself as 10- to 40-year cycles in the upper-ocean temperature and swings between the dominance of northern, "fatty" zooplankton and southern, "skinny" zooplankton (Mackas et al., 2001; Peterson and Schwing, 2003) (**Figure 2D**).

Over the last 15 years, PNW waters have been exposed to hypoxic and even anoxic events (Grantham et al., 2004; Hales et al., 2006; Chan et al., 2008) that have the potential to severely disrupt local fisheries. Upwelled waters are both low in oxygen and high in dissolved inorganic carbon dioxide (DIC), making PNW coastal waters particularly vulnerable to ocean acidification (OA; Feely et al., 2008). OA results in low pH and carbonate-mineral stability (**Ω**). Further increases in DIC, from the decay of upwelling-fueled plankton blooms on the continental shelf, drives pH even lower (Feely et al., 2016, 2018; Bednaršek et al., 2017). These low-**Ω** waters harm the development of oyster and mussel larvae (Waldbusser et al., 2015), and leads to failures in larval production in the PNW shellfish hatcheries that support the majority of west coast shellfish growers (Barton et al., 2012, 2015). The region is also known for the appearance of harmful algal blooms (HABs) which generate toxic substances that become incorporated into the ocean food chain, leading to the closure of valuable commercial, subsistence, and recreational fisheries. Recently, warm blob waters were identified as contributing to an enhanced HAB in the area (McCabe et al., 2016; McKibben et al., 2017), specifically the toxic diatom bloom (*Pseudo-nitzschia*) that produces the toxin, domoic acid. These toxic cells were ingested by the iconic and valuable Dungeness crab (*Cancer magister*) resulting in the economically devastating, coastal-wide closure of this fishery.

Bounding the western part of the Juan de Fuca Plate in the NEP, is a linear chain of underwater volcanoes. Here, the Juan de Fuca (JdF) spreading center is part of the mid-ocean ridge system that accounts for >70% of the volcanism on Earth. Studying these underwater volcanoes provides insight on the processes that form oceanic crusts and the role of submarine volcanoes in exchanging heat and chemicals with the ocean (Kelley et al., 2016; Wilcock et al., 2018). Underwater volcanoes also support chemosynthetic biological communities. Axial Seamount is the most magmatically robust volcano on the Juan de Fuca ridge and erupted in 1998 and 2011, and most

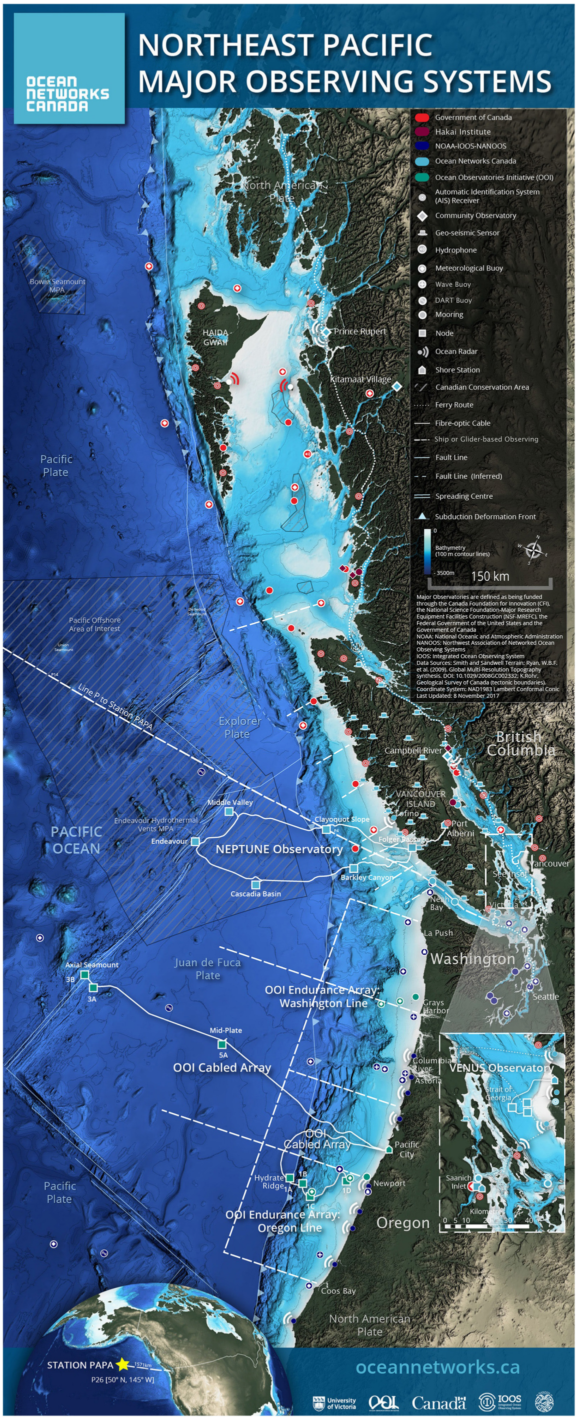


FIGURE 1 | Map of the ocean observing assets in the Northeast Pacific. Colors indicate ocean observing assets funded by the Canadian (red) and United States governments (dark blue), by the private Hakai Institute (maroon), and by two major ocean observing programs: Ocean Networks Canada (light blue) and the Ocean Observatories Initiative (teal). Buoys and shore-side infrastructure are shown as distinct symbols, while ship or glider lines (dashed) and instrumented ferry routes (dotted) are shown as continuous curves. Seafloor cables are shown as curvy, solid lines. Bottom depth, in meters, is shaded in blue. Courtesy of Ocean Networks Canada as modified by C. Risien (OSU).

recently in 2014, resulting in a lava flow 127 m thick (Chadwick et al., 2016) (**Figure 2F**). Between eruptions, magma recharges beneath the summit caldera, leading to steady inflation and increasing rates of seismicity. During each eruption, the volcano deflates over days to weeks.

There is keen interest in understanding seismic activity in the Cascadia Subduction Zone and the subsequent potential for local tsunamis. While seismic activity is measured with cabled and uncabled ocean bottom seismometers, the signatures of tsunami waves are measured with high-precision bottom pressure recorders. These bottom pressure sensors can also detect waves associated with remotely generated tsunamis. These open-ocean observations are uncontaminated by coastal effects, such that local seafloor bottom pressure records from future tsunami events may be used as real time input to a regional numerical tsunami forecast model (Thomson et al., 2011).

This review begins with a description of various ocean observing efforts in the NEP that span from offshore and deep ocean to measurements being made in estuaries and at the coast. The observing techniques include measurements made from ships and ferries, moorings, cabled and land-based sensors, and autonomous underwater gliders. A description of ocean modeling in the region is provided next, followed by a discussion on how we endeavor to make both measurements and models useful to ocean users. We summarize this by looking to the future.

NORTHEAST PACIFIC OCEAN OBSERVING: OPEN OCEAN TO SHORE

Waters of the NEP change on time scales from hours to decades, requiring ocean sensors to collect samples at minute intervals and deploying these on to platforms designed and operated for decades. Ocean observing assets in the NEP span from Station Papa in the central Gulf of Alaska, across the continental slope and shelf from British Columbia to Oregon, into major estuaries and inland seas, and to the shore (**Figure 1**). For a list of NEP ocean observing programs, their acronyms, pointers to their web pages, and a list of the coauthors and key contributors involved with each program, see **Table 1**.

The farthest offshore, open-ocean observing elements in the NEP are associated with Ocean Station Papa (50°N, 145°W), and include moorings operated by the United States National Science Foundation (NSF) funded Ocean Observatories Initiative (OOI) and the National Oceanic and Atmospheric Administration (NOAA), and the Line P hydrographic line occupied by Fisheries and Oceans Canada (DFO). The coastal and regional ocean observing network in the NEP includes DFO's La Perouse monitoring program, NOAA's Newport Hydrographic Line, the OOI's Endurance and Cabled Arrays, Ocean Networks Canada's NEPTUNE and VENUS arrays, and the Northwest Association of Networked Ocean Observatories (NANOOS), and the regional association of the United States Integrated Ocean Observing System (IOOS) supported by NOAA. Closest to shore are the shore-based and cabled oceanographic monitoring stations operated by the United States and Canadian governments, the private Hakai Institute, and by Native American Tribes

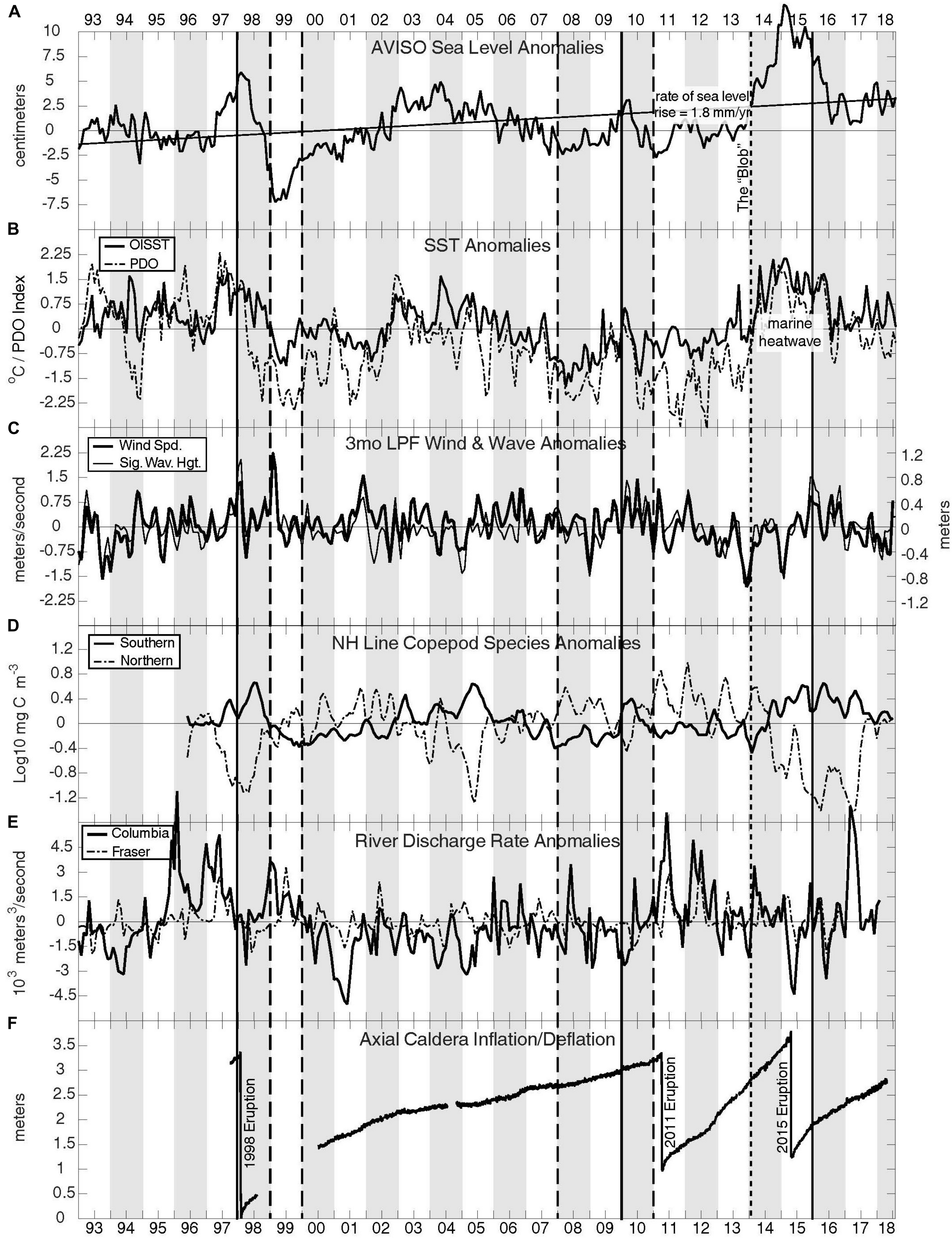


FIGURE 2 | Northeast Pacific anomalies showing interannual and interdecadal variability over the last 25 years: **(A)** AVISO blended satellite sea level; **(B)** Sea Surface Temperature and Pacific Decadal Oscillation; **(C)** 3-month filtered surface winds and significant wave height; **(D)** zooplankton (copepod) species indices; **(E)** Columbia and Fraser River discharge; and **(F)** Axial Volcano inflation/deflation measurements. Strong El Niño (solid) and La Niña (dashed) events are indicated, as is the "warm blob." A significant 1.8 mm year^{-1} rise in sea level is indicated in the top panel. The satellite and model output are spatially averaged (45–50°N, 125–130°W) monthly anomaly fields. The copepod species anomalies are from the Newport, Oregon, Hydrographic Line (44° 39.1′N). See **Table 2** for data sources.

TABLE 1 | List of Northeast Pacific ocean observing systems and models.

Ocean observing system asset or Model	Country	Affiliated author(s)*	URLs
Ocean Observatories Initiative (OOI)	United States	Barth, Dever, Fram, Kawka, Kelley, Risien, Wingard	https://oceanobservatories.org/
Ocean Networks Canada (ONC)	Canada	Dewey, Juniper	http://www.oceannetworks.ca/
Northwest Association of Networked Ocean Observing Systems (NANOOS)	United States	Barth, Hales, Kosro, Kurapov, Mayorga, MacCready, Newton, Risien, Shearman, Siedlecki	http://www.nanoos.org/ http://ingria.coas.oregonstate.edu/rtdavow/
SalishSeaCast	Canada	Allen	https://salishsea.eos.ubc.ca/
Hakai Institute	Canada	Evans, Jackson	https://www.hakai.org/
Pacific Marine Environmental Laboratory Carbon Group (NOAA-PMEL)	United States	S. Alin[#], A. Sutton[#], Feely	https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Newport Hydrographic Line (NOAA)	United States	Fisher, K. Jacobson[#]	https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/index.cfm
Pacific Northwest HAB Bulletin (NOAA)	United States	Trainer	http://www.nanoos.org/products/habs/forecasts/bulletins.php
University of Washington LiveOcean Model	United States	MacCready, Siedlecki	https://faculty.washington.edu/pmacc/LO/LiveOcean.html
Line P/La Perouse monitoring programs	Canada	Ianson, Perry, Robert, Ross	https://www.waterproperties.ca/linep/index.php
Quinault Nation HAB sampling, water quality monitoring nearshore	Quinault Indian Nation	Schumacker	http://qlandandwater.org/departments/fisheries/marine-resources/
Tsleil-Waututh-Ocean Networks Canada Burrard Inlet Monitoring Initiative^	Tsleil-Waututh Nation	Konovsky	https://www.oceannetworks.ca/ocean-networks-canada-partners-tsleil-waututh-nation-monitor-burrard-inlet
Canadian Pacific Robotic Ocean Observing Facility (C-PROOF)^	Canada	Klymak, Waterman	http://valdez.seos.uvic.ca/~jklymak/ https://www.eoas.ubc.ca/people/stephaniewaterman

Listing is alphabetical; see co-author list for full names and affiliations. ^Planned ocean observatory asset. #Additional key contributor not included in the author list; see URLs for full author names.

and First Nations. This combination of ocean observatories affords an exceptional opportunity to study the eastern boundary current and coastal ocean processes, within the context of regional climate and ocean changes. NOAA's Pacific Marine Environmental Laboratory's carbon group is working with a number of academic and government partners to conduct large-scale coastal surveys and underway measurements of OA, to determine spatial scales of carbon dioxide sources and sinks, and causes thereof, along the entire west coast of North America. These surveys have taken place every few years since 2007 (Feely et al., 2008, 2016).

Hydrographic and Net Sampling

The Line P program was created in 1956, by adding regular physical and chemical oceanographic observations on the weather ship already transiting regularly to Ocean Station Papa[1] (Whitney and Tortell, 2006). The La Perouse program started in 1979, as a means to monitor the physical and biological characteristics of the ocean immediately west of Vancouver Island, and to relate these characteristics to the recruitment of various fish species that comprise some of the major commercial fisheries (Mackas, 1992). In 1999, Strait of Georgia Surveys were added (Masson, 2006). More regular chemical and biological observations were added over time to all three programs (e.g., Whitney et al., 2005; Tortell et al., 2012; Ianson et al., 2016). The Newport Hydrographic Line (44° 39.1'N) has a history of observations extending back to 1961 (Huyer et al., 2007). Bi-weekly biological sampling for zooplankton begun on the Newport Hydrographic Line in 1996 (Fisher et al., 2015). These monitoring programs have long-formed the base upon which many process studies have been launched. These studies have wide-ranging interests from air-sea interactions, to mixed-layer dynamics, plankton ecology, iron depletion and enrichment, and seabird populations. A recent example includes the first phase of the NASA/NSF funded EXPORTS project which quantifies the export and fate of upper ocean net primary production at Ocean Station Papa[2].

Vancouver Island and Strait of Georgia Moorings

The Institute of Ocean Sciences (DFO) has maintained three autonomous moorings along the continental shelf off Vancouver Island for over 30 years and one mooring in the Strait of Georgia for 10 years. This array has recently been extended north into Queen Charlotte Sound, Hecate Strait, and Chatham Sound. The typical properties measured are temperature, salinity, dissolved oxygen and current velocity. In 2018, biological settling plates were installed as part of a systematic effort to monitor aquatic

[1] https://waterproperties.ca/linep/history.php

[2] http://oceanexports.org/

TABLE 2 | Data sources for **Figure 2**.

AVISO Sea Level Anomaly: Blend of TOPEX/Poseidon, Envisat, Jason-1, and OSTM/Jason-2 satellite altimetry measurements; https://www.ocean-sci.net/12/1067/2016/; Pujol et al. (2016).
Optimum Interpolation Sea Surface Temperature (OISST); analysis constructed by combining observations from satellites, ships, and buoys; https://www.ncdc.noaa.gov/oisst; Reynolds et al. (2007).
Pacific Decadal Oscillation (PDO); https://www.ncdc.noaa.gov/teleconnections/pdo/; Mantua et al. (1997).
North American Regional Reanalysis (NARR) winds: https://www.esrl.noaa.gov/psd/data/gridded/data.narr.html; Mesinger et al. (2006).
Wave Watch 3 significant wave height: http://www.cawcr.gov.au/technical-reports/CTR_070.pdf; Durrant et al. (2014).
Copepod species anomalies: https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/eb-copepod-anomalies.cfm; Fisher et al. (2015).
Columbia River discharge at Port Westward, Oregon: https://waterdata.usgs.gov/nwis/monthly/?search_site_no=14246900&agency_cd=USGS&referred_module=sw&format=sites_selection_links
Fraser River at Hope, British Columbia: https://wateroffice.ec.gc.ca/report/historical_e.html?stn=08MF005
Axial Volcano inflation/deflation data: ftp://ftp.pmel.noaa.gov/newport/chadwick/4scott/LTplot-files/; Nooner and Chadwick (2016).

invasive species in offshore waters. In August 2018, a coastal surface mooring with a water column profiler was installed in the central Strait of Georgia.

Ocean Observatories Initiative Coastal and Cabled Arrays

The OOI Endurance Array is built using a variety of oceanographic sampling platforms including surface moorings, water column profilers, and instruments on the sea floor as well as on a mid-water platform (Kelley et al., 2016; Barth et al., 2018). The Endurance Array backbone includes the Oregon Line, off Newport near 44.6°N, and the Washington Line, off Grays Harbor near 47°N (**Figure 1**). These lines each have three sites: the inner shelf site ∼25–30 m water depth and 4–6 km from the shore; the mid shelf site ∼80–90 m water depth and 20–30 km from the shore; and the continental slope site ∼500–600 m water depth and 60–65 km from the shore. All EA platforms and sites measure fundamental ocean properties like temperature, salinity, pressure, water velocity, chlorophyll fluorescence, and dissolved oxygen. Many surface and water-column platforms host sensors measuring CO_2 partial pressure (pCO_2), both in water and in the atmosphere above, pH, spectral light absorption and attenuation, incoming spectral radiation, and nutrients. Cabled echo sounders that obtain acoustic backscatter from targets in the water column, including zooplankton and fish, sample continuously at the Oregon shelf and offshore sites at three-frequencies (38, 120 split beam, and 200 kHz). Uncabled, autonomous 4-frequency echo sounders (38, 125, 200, and 455 kHz) are mounted to the bottom of each Endurance Array mooring.

Coastal surface moorings consist of a surface buoy with local wind and solar power generation and are equipped with meteorological instruments that provide continuous measurements of winds, air temperature and humidity, and solar radiation at 1-min intervals. A mooring line supports the delivery of power and data to instruments along the line and an instrumented seafloor platform. The Endurance Array sensors and platforms return data to shore via a cellular or satellite link at the sea surface for autonomous moorings or seafloor cables shared with the OOI Cabled Array (see next paragraph). Data are available at https://oceanobservatories.org/.

The OOI Cabled Array consists of two legs heading offshore from Pacific City, Oregon (**Figure 1**). The Cable Array provides unprecedented power (10 kV, 8 kW) and bandwidth (10 Gigabit Ethernet), and two-way communication to scientific sensor arrays on the seafloor and throughout the water column (Kelley et al., 2016; Smith et al., 2018). One leg goes west for ∼500 km, spanning the Juan de Fuca Plate, to host a multi-platform, instrumented underwater laboratory at the base and summit of the Axial Seamount (**Figure 2F**). Cabled infrastructure at the summit of the volcano is comprised of the most advanced submarine volcanic observatory in the oceans. Here, a diverse array of geophysical, chemical, and biological sensors/samplers, as well as a high-definition cameras and digital still cameras, provide real-time information on linkages between seismic events, fluid flow, and changes in biological communities. Application of the real-time data provided by the Cabled Array was highlighted by the 2015 eruption that was marked by >8,000 earthquakes and a concomitant drop in the seafloor by 2.4 m on April 24, 2015, followed by >30,000 explosions, heating of waters within the caldera, and explosive ash-generating events (Nooner and Chadwick, 2016; Caplan-Auerbach et al., 2017; Wilcock et al., 2018; Xu et al., 2018). At the base of the volcano, water-column sensors are deployed on cabled moorings with instrumented wire-following profilers, and state-of-the-art two-legged moorings that provide 3 kW power and 1 GB communication to instrumented platforms at 200-m depth, and to instrumented winched profilers.

A second OOI cable leg loops south from Pacific City and hosts infrastructure on the Southern Hydrate Ridge (SHR) site to provide insight into actively venting methane hydrate systems (Kelley et al., 2016). Processes of interest include the temporal evolution of methane hydrate systems in response to seismic events, determining chemical fluxes from the seafloor and impacts on overlying ocean chemistry, and understanding biogeochemical coupling associated with gas-hydrate formation and dissolution (Philip et al., 2016). Since 2016, significant instrument expansion of the Axial and SHR sites has occurred through funding by NSF, United States Office of Naval Research, and Germany. The cable continues up the continental slope and shelf to connect to the OOI EA offshore (587 m) and shelf (80 m) sites.

Profiling Moorings

Northeast Pacific observatories host cutting-edge profiling moorings that use self-contained instrument packages that move up and down through the water column to provide fine vertical resolution (∼1 m) at fixed stations. The OOI hosts several types of vertical profilers including both autonomous and cabled wire-following profilers that carry low-power instruments from just below a subsurface float at ∼30-m depth down to a maximum specified depth (~500 m for Endurance Array, ~2,500 m for Cabled Array) ascending and descending many times per day. Two types of shallow winched profilers are deployed by OOI, including one type on the Cabled Array 200-m platforms that profiles the water-column to just beneath the sea surface, using a sensor package that transmits data back in real-time via a cable (Kelley et al., 2016; McRae, 2016). Since 2015, the three Cabled Array winched science pods have obtained >30,000 profiles. Communications conducted at the speed of light, from shore, allow adjustments to be made to profiling missions that include documentation of thin layers, storms, and major subsurface currents that result in blow down of the 7,000-lb, 12-ft across platforms 200 m beneath the surface. A Coastal Surface Piercing Profiler (CSPP) is deployed at the Endurance Array shelf and inshore sites and profiles from near the sea floor to the sea surface where it returns data to shore via Iridium satellite. The CSPP rises toward the sea surface under positive buoyancy and then, after reaching the sea surface, is winched back down to near the seafloor where it resides until the next profile. A nearby surface coastal mooring is equipped with an acoustic modem so that the CSPP can be commanded from shore to not profile in the case of large (>3 m) surface waves.

Ocean Networks Canada

Ocean Networks Canada (ONC) is committed to continuous, long-term recording of temperature, salinity, water velocity, dissolved oxygen, pH and pCO_2 using sensors installed on the North East Pacific Time-series Underwater Networked Experiments (NEPTUNE) observatory (**Figure 1**). Data are sent to shore via an 840-km loop of fiber optic cable with five nodes[3]. Each node is instrumented with a diverse suite of sensors that enable researchers to study interactions among geological, chemical, physical, and biological processes that drive the dynamic Earth-ocean system over a broad spectrum of oceanic environments including the continental shelf at Folger Passage, the continental slope at Clayoquot Slope and the Barkley Canyon, the mid-plate on the abyssal plain at Cascadia Basin, a mid-ocean ridge at the crest of the Endeavour Segment of the Juan de Fuca Ridge, and the axial rift valley at Middle Valley.

Ocean Networks Canada sensors are also installed throughout the Salish Sea with cabled systems in the Saanich Inlet, naturally anoxic at depth through much of the year, and in the Strait of Georgia, comprising of the Victoria Experimental Network Under the Sea (VENUS) (**Figure 1**). The Fraser River delta in the Strait of Georgia is an ideal location for examining sedimentation processes. Sensors installed on two VENUS nodes (at Central and East Strait of Georgia) are able to measure variables that can affect slope stability and observe what mechanisms regulate underwater landslides in near real-time. ONC also operates a variety of non-cabled observing systems in the Salish Sea (**Figure 1**).

From the very beginning, a central pillar for ONC has been the development of the Oceans 2.0 data management system[4]. ONC has made and continues to make investments in the management of data collection, metadata management, and data delivery services. Approximately one-third of the ONC staff have always been devoted to data management, including a core systems and operations group, a software development team, a data quality and data product department, and finally a team in charge of managing metadata. While a few users require near real-time data access, the majority demand high quality and reliable data archive access, including comprehensive metadata management services.

The OOI and ONC offshore cabled arrays were originally planned to be connected offshore to provide a redundant power and data path in case of cable failure in one of the two systems. This did not happen because of a mismatch in the timing for the funding of the two systems. Achieving such a desirable engineering goal in the future for systems in the NEP or elsewhere will require concerted, advanced planning.

Northwest Association of Networked Ocean Observing Systems

The Northwest Association of Networked Ocean Observing Systems (NANOOS) is the IOOS regional association in the PNW, serving primarily Washington and Oregon. NANOOS has five areas of emphasis: climate, coastal hazards, ecosystem assessment, fisheries and biodiversity, and maritime operations[5]. Initiated by academic oceanographers and built through public engagement of groups with ocean and estuarine interests, NANOOS's governing council includes representatives of all 66-member organizations from academia/research, federal/state/local government, tribal government, industry, and non-governmental organizations.

Northwest Association of Networked Ocean Observing Systems coordinates the collection of ocean and estuary data from a wide network of offshore buoys, estuarine stations, underwater gliders, shore stations and instrumented ferries (**Figure 1**). These include approximately 40 monthly stations in the United States part of the Salish Sea collected for nearly three decades by the Washington Department of Ecology and the summer-season moorings near the northern coast of Washington, deployed by NOAA's Olympic Coast National Marine Sanctuary. NANOOS combines data it collects and regional model output with observations from local (including, for example, Washington King County, Washington Department of Health, Pacific Shellfish Institute, Penn Cove Shellfish, Taylor Shellfish, Hakai Institute) and regional partners (OOI and ONC), and with that from other NOAA observing assets, satellites, and regional and global-scale models, and Environment Canada moorings, and distributes them via the NANOOS Visualization System[6] as well as to nationally integrated IOOS systems. NANOOS data are accessed by a variety of ocean users including fishers, resource managers, marine pilots and academics.

Land-Based Coastal Radar

Northwest Association of Networked Ocean Observing Systems operates land-based coastal radar stations (CODAR) that provide ocean surface currents out to about 150 km offshore along

[3]http://www.oceannetworks.ca/

[4]http://www.oceannetworks.ca/innovation-centre/smart-ocean-systems/ocean-observing-systems/oceans-20

[5]urlhttp://www.nanoos.org/

[6]http://nvs.nanoos.org

the coast of Oregon (**Figure 1**). Surface current maps are provided to ocean users for navigation, to NOAA's Office of Response and Restoration, and to the United States Coast Guard Search and Rescue. Surface current maps are assimilated into regional ocean circulation models (see below). Expansion is underway to extend land-based radar coverage up the Washington State coast and, in collaboration with ONC, to improve coverage in the Strait of Juan de Fuca. ONC also operates land-based coastal radars. A WERA system is installed at Tofino Airport, Vancouver Island, and provides maps of ocean surface currents and significant wave height and direction over long distances offshore. ONC has also installed coastal Wave Radar (WAMOS) and Coastal Radar (CODAR) systems in the Strait of Georgia and also in partnership with communities on British Columbia's north coast and on Haida Gwaii. PNW coastal radar data are integrated and redistributed by the IOOS High-Frequency Radar Data Assembly Center (HF Radar DAC).

Underwater Gliders

There is an extensive underwater glider network in operation in the NEP (**Figure 1**). Sensors onboard the gliders measure temperature, salinity, pressure, dissolved oxygen, chlorophyll and colored dissolved organic matter fluorescence, light backscatter, and depth-averaged velocity. Data are reported to shore by the Iridium satellite cell phone and made available via various data servers (NANOOS NVS, OOI, IOOS GliderDAC). Glider sampling started off La Push, WA, United States, in 2003 using a University of Washington Seaglider. Regular glider observations along the Newport Hydrographic Line, OR, United States, using Teledyne Webb Research Slocum gliders and Seagliders started in spring 2006 (Adams et al., 2016; Saldias et al., 2016) and continues through to the present day under funding from OOI. The OOI glider network adds a second, ∼300-km long cross-margin, glider-monitored section off Grays Harbor, WA, United States, with shorter cross-margin lines from La Push, WA, United States, to Coos Bay, OR, United States. Since 2014, a NANOOS-supported glider line has been operating off Trinidad Head, CA, United States (41.1°N), connecting the NEP glider array to the central and southern California glider array farther south. Future glider lines are planned off Vancouver Island as part of the recently funded Canadian Pacific Robotic Ocean Observing Facility.

Ferry-Based Systems

Flow-through and meteorological measurement systems are installed in many regularly scheduled passenger ferries in the NEP including in Puget Sound and the Strait of Juan de Fuca, operated by the Washington State Department of Transportation and Clipper Vacations, in the Strait of Georgia, operated by BC Ferries, and off northern British Columbia and into Alaska, operated by the Alaska State Ferry system (**Figure 1**). Sensors measure oxygen, temperature, salinity, turbidity, chlorophyll, and organic matter and data are transmitted to shore stations via a Wi-Fi connection.

Shore and Estuarine Stations

Shore and estuarine stations measure sea level, e.g., NOAA and Canadian Hydrographic Service tide gauges, and water properties, often in cooperation with coastal communities. These "community observatories" are motivated by local ocean challenges, e.g., OA, and the need for information, and often funded locally. Instrumentation and data delivery are coordinated through the larger NEP ocean observing systems (NANOOS, ONC). Shore stations include a diversity of sensors including temperature, salinity, nutrients, phytoplankton biomass, pH, pCO_2, DIC, carbonate mineral stability, and other metrics of OA. Examples of shore stations are at Campbell River, northern Vancouver Island, on Kwakwaka'wakw and Coast Salish Territory operated by ONC, and on nearby Quadra Island at the northern end of the Strait of Georgia operated by the privately funded Hakai Institute. There are 10 other stations that monitor metrics of OA between Carlsbad, California, and Kodiak, Alaska. A future shore station is planned for Burrard Inlet by the Tsleil-Waututh Nation in collaboration with ONC. Earthquake-detecting accelerometers are installed and operated by ONC at many Vancouver Island stations. Weather stations are also installed at many shore sites.

OCEAN MODELING AND FORECASTING

There are several regional coastal and inland sea models in use for PNW waters. These stretch from Vancouver Island, Canada, to southern Oregon or farther into northern California. They are forced by numerical weather models and obtain boundary conditions from a variety of basin-scale ocean models. Most of the models are based on the Regional Ocean Modeling System[7] (Haidvogel et al., 2000). A common goal is to accurately represent flow-topography interactions by using high spatial resolution to represent coastline and bottom topographic features. Some models are purely physical, while others include marine ecosystem modules, the latter sometimes including carbon and oxygen dynamics. Output from all these models is integrated into NANOOS NVS for wider, user-friendly access.

The Oregon State University coastal ocean forecast system for PNW waters produce daily updates of 3-day forecasts of the currents, temperature, salinity, sea surface height, and other dynamic information at 2-km resolution[8] (**Figure 3**). The wind and surface heat flux forcings are obtained from NOAA's North American Mesoscale weather forecast model. Information about the surrounding ocean comes from a lower-resolution global Navy prediction system. The accuracy of the oceanic forecasts is improved through assimilation of surface currents measured by land-based coastal radars, and satellite sea surface temperature and satellite sea-surface height (Kurapov et al., 2011; Yu et al., 2012). This methodology was transitioned to NOAA where the West Coast Operational Forecast System (WCOFS), spanning the entire United States West Coast, is being developed and tested (Kurapov et al., 2017).

[7] www.myroms.org

[8] http://ingria.coas.oregonstate.edu/rtdavow/

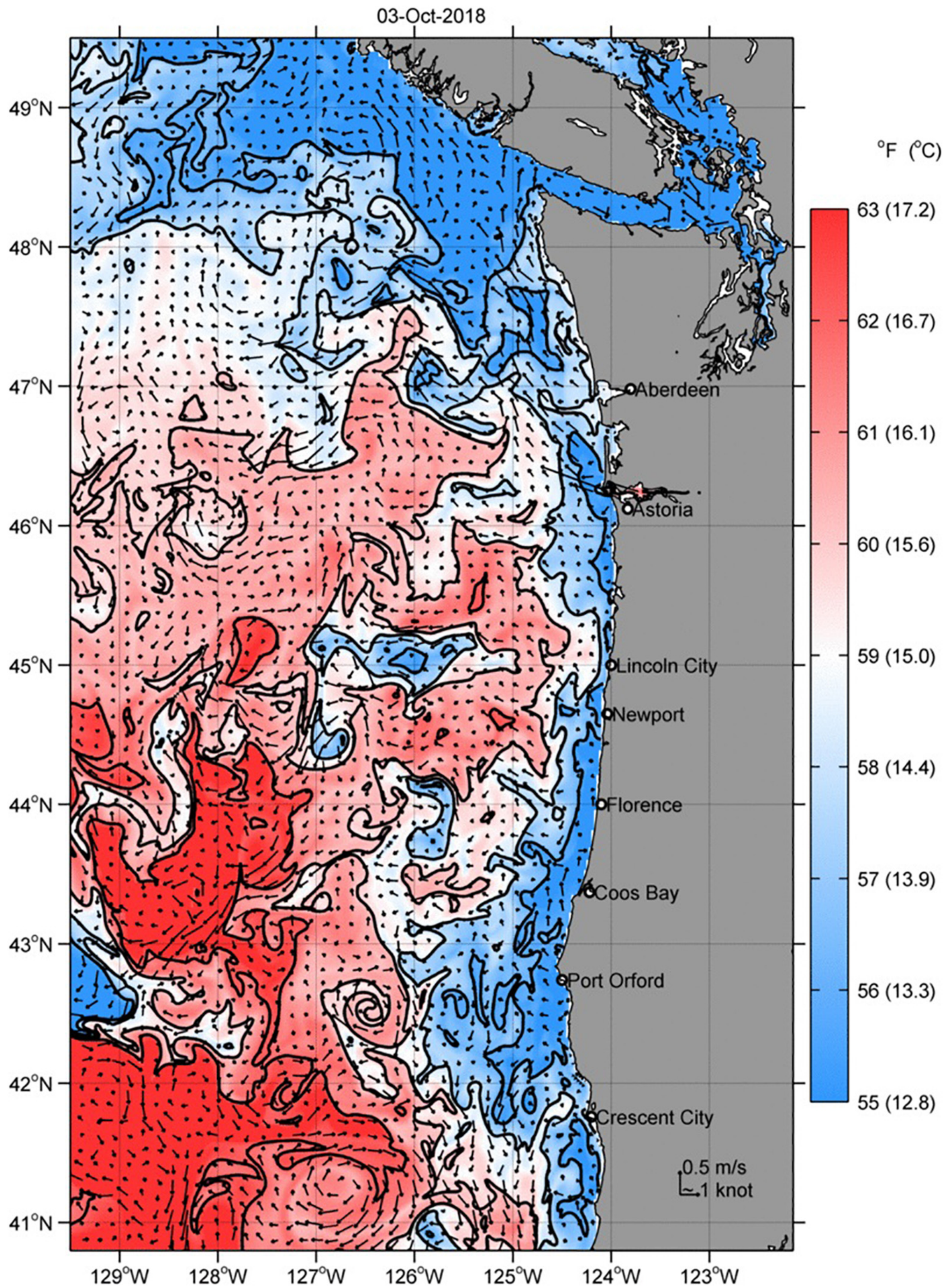


FIGURE 3 | Numerical ocean circulation model nowcast of sea surface temperature off the Pacific Northwest. The color bar is tailored to highlight the location of the 59° Fahrenheit contour, the temperature used by albacore tuna (*Thunnus alalunga*) fishermen to identify the boundary between cold, upwelled waters and offshore, warm waters where tuna is more likely to be found. Produced by A. Kurapov's group at OSU and NOAA, and available on the NANOOS Visualization System, http://nvs.nanoos.org/TunaFish.

The SalishSeaCast model operated at the University of British Columbia is a coupled physical-biogeochemical model for the Salish Sea[9]. Model output is used to predict storm surge for the Strait of Georgia (Soontiens et al., 2016), with storm surge advisories published on the web and pushed to Port Metro Vancouver (**Figure 4**). Efforts are also underway to create oil spill risk maps and to make sea surface height and current predictions useful for search and rescue and vessel pilots.

[9]https://salishsea.eos.ubc.ca/

Another active modeling program at the University of Washington is LiveOcean, that simulates ocean water properties in the NEP and Salish Sea[10]. The model provides 3-day forecasts of aragonite saturation states and pH of waters entering shellfish growing areas on the coast. The model system is built using existing 3D circulation-biogeochemistry hindcast models, incorporating carbon chemistry (Davis et al., 2014; Siedlecki et al., 2015). The modeling has been successful because of its links to the strong NEP observational and stakeholder community. As one stakeholder example, resource managers from Washington and Oregon use LiveOcean forecasts as part of a system to decide whether to close shellfish harvest at the coast in response to HAB (Giddings et al., 2014; and see below).

Northwest Association of Networked Ocean Observing Systems serves output from all three of these models, OSU ROMS, UBC Salish SeaCast, and UW LiveOcean, from its NVS portal, allowing users to compare outputs. A "comparator" feature allows for comparison of model output with the real-time data.

MAKING MEASUREMENTS AND MODELS USEFUL

It is a shared goal in the NEP to make ocean data and model output useful to ocean users, educators, policy makers and the public. By engaging with ocean users, we work to display and make available ocean measurements and model output. Engagement with ocean users is critical and continual iteration and refinement leads to the best results. Examples of ocean and model "products" are found at the web sites of NEP observing and modeling efforts (**Table 1**). As one example (see **Figure 3**), ocean circulation model surface temperature nowcast and forecast fields are redrawn using a red-blue color scale to highlight the 59° Fahrenheit contour, the temperature used by albacore tuna (*Thunnus alalunga*) fishermen to identify the boundary between cold, upwelled waters and offshore, warm waters where tuna are more likely to be found[11]. The value of these model fields is evident in YouTube videos by fishermen explaining to their fellow fishers how to access and use these fields[12]. A second example (see **Figure 4**), is the storm surge advisory issued for the major urban area of Vancouver, BC, United States produced from a numerical ocean circulation forecast model[13]. A final example is a twice-monthly, web-based bulletin for the early warning of PNW coast HAB events[14]. Forecasts based on LiveOcean are intended to help resource managers from Neah Bay, WA, United States, to Newport, OR, United States, to target their beachside monitoring of toxicity levels in shellfish and fine-tune decisions regarding closures of beaches to shellfish harvest.

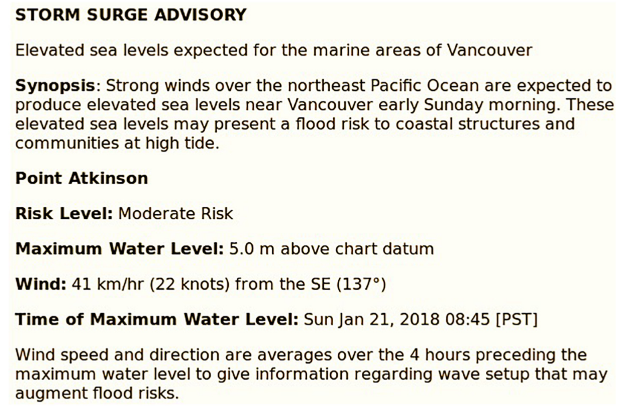
[10]https://faculty.washington.edu/pmacc/LO/LiveOcean.html

[11]http://nvs.nanoos.org/TunaFish

[12]https://www.youtube.com/watch?v=SctTzbZ-1us

[13]https://salishsea.eos.ubc.ca/storm-surge

[14]http://www.nanoos.org/products/habs/forecasts/bulletins.php



STORM SURGE ADVISORY

Elevated sea levels expected for the marine areas of Vancouver

Synopsis: Strong winds over the northeast Pacific Ocean are expected to produce elevated sea levels near Vancouver early Sunday morning. These elevated sea levels may present a flood risk to coastal structures and communities at high tide.

Point Atkinson

Risk Level: Moderate Risk

Maximum Water Level: 5.0 m above chart datum

Wind: 41 km/hr (22 knots) from the SE (137°)

Time of Maximum Water Level: Sun Jan 21, 2018 08:45 [PST]

Wind speed and direction are averages over the 4 hours preceding the maximum water level to give information regarding wave setup that may augment flood risks.

FIGURE 4 | Example of a storm surge advisory for the major Pacific Northwest urban area of Vancouver, BC, Canada. The advisory is produced by a numerical ocean circulation forecast model run by S. Allen (University of British Columbia) and is available at https://salishsea.eos.ubc.ca/storm-surge.

SUMMARY AND A LOOK TO THE FUTURE

We are fortunate to have a wide range of ocean and seafloor observing assets in the NEP that provides data which adds to longstanding climatologies for the region and that are used to verify and drive ocean circulation and biogeochemical models. The NEP is home to a subduction zone ripe for a magnitude > 8, tsunami-generating earthquake and underwater volcanoes that bound one of the smallest tectonic plates on Earth, the Juan de Fuca plate. Recently, thousands of methane seep sites underlain by gas hydrates have also been discovered along the margin, with unknown impacts on release of greenhouse gas and associated ecosystems. For these reasons, and because of the recent dramatic adverse effects on marine ecosystems from hypoxia, OA and HABs, we dedicate ourselves to maintaining, expanding, improving and integrating the ocean observing system and modeling of the NEP.

There are several examples of cooperation across borders to enhance ocean observing in the NEP. The continued time series at Ocean Station Papa are a result of Canadian and United States coordination of mooring systems, locations, servicing, and field measurement programs. The two large offshore NEP cabled observatories, the OOI Cabled Array and ONC's NEPTUNE, coordinated placement of cabled measurement nodes along the Juan de Fuca plate and at the subduction zones off Oregon and Vancouver Island, respectively. Many of the oceanographic sensors used across the NEP observing assets are the same or similar, e.g., Conductivity-Depth-Temperature instruments from Sea-Bird Scientific and dissolved oxygen optodes from Aanderaa Data Instruments and are deployed in similar manners. We suggest that this is implicit rather than explicit coordination, but at least demonstrates the commonality of science issues and available instrumentation. It has also been advantageous to have cross-border representation of scientists on some governing boards and oversight committees. Examples of this are United States scientists serving on ONC's International Science Advisory Board and tribal representation on NANOOS's Governing Council. Committee members can help cross-pollinate the latest ideas and new measurement techniques between observatories and can help guide the addition of new ocean observing capabilities needed to address their concerns.

Even with this degree of cooperation, there is room for improvement. For example, there could be more coordination on the placement (water depth), functionality and sampling protocols amongst the coastal ocean moorings across the NEP. Data are handled and distributed with different approaches, for example the Canadian data are distributed through a relatively sophisticated, centralized ONC data system while United States data are available across a variety of distribution platforms (OOI, NOAA NODC, NANOOS). There is room for improved coordination on instrument types, sampling, biofouling protection, best practices, metadata, and data quality assurance and control, etc. Activities for this coordination are becoming more routine and should be encouraged, for example, the North Pacific Marine Science Organization's (PICES) Advisory Panel on North Pacific Coastal Ocean Observing Systems and the inaugural March, 2018, National Coastal Ecosystem Moorings Workshop, organized and hosted by the Alliance for Coastal Technologies and sponsored by IOOS. We are eager to make continued improvements in these areas.

The many needed and planned improvements and expansions of ocean observing and modeling in the NEP are discussed next. A gap in sampling of shelf break processes off Vancouver Island is targeted to be filled soon by regular glider transects. Although some systems are in place, we need to improve our ability to make accurate long-term surface and subsurface measurements of chemical properties and rates. We also need information on the causes of variability in phytoplankton community structure, as well as growth rate information for both phyto- and zooplankton. Another need is the automated physical sampling of phytoplankton at HAB initiation sites such as the Juan de Fuca Eddy, WA, United States, and Heceta Bank, OR, United States. A pilot program by IOOS tested an autonomous underwater vehicle to sample the Juan de Fuca Eddy, with samples delivered to the Makah Tribal analytical lab for measurement of domoic acid and HAB cells. Finally, events such as the Tohoku, Sumatra, and Chilean earthquakes and resultant tsunamis that resulted in the loss of thousands of lives and billions of dollars of damage, serve as an important impetus to increase seismic and tsunami monitoring systems offshore that could feed into NOAA as well as the recently implemented Shake Alert system[15].

We have been fortunate to interact with ocean users, international partners, policy makers and private foundations in seeking support for our ocean observing and modeling. We expect the mix of public and private funding to continue into the future but anticipate the day when ocean data and model forecasts are used and increasingly supported by entities that directly benefit from their use. While some of this is happening now, e.g., surf forecasts from Surfline[16], there is great potential for the use of ocean data and models in "value added" products that are routinely used by ocean users. It is imperative for us to continue to "seatruth" our ocean models, in particular forecasts of ocean biogeochemical properties like dissolved oxygen and pH (aragonite saturation). We will continue to interact with ocean users to improve our data delivery and derived products. NEP observing systems can be made more efficient by targeting observing assets to key locations identified through ocean observing system simulation experiments.

In addition to our oceanographic fleets and government and academic modeling groups, there are other sources of data to develop. Several examples of "citizen science" are found in the NEP, including a "Netflix" model – based on the original Netflix approach of DVD rental by mail – for placing and regularly exchanging robust pH sensors in Oregon's Marine Reserves[17]. As ocean sensors become more robust and affordable, there are more ways to get citizens involved in monitoring our environment. While some ferries plying NEP, waters are instrumented with flow-through systems that return data to shore, there is opportunity to partner with the commercial and recreational fishing communities to make cost-effective ocean observations.

Lastly, in addition to continuing to use our data, models and understanding to inform public policy, we dedicate ourselves to sharing and delivering ocean and seafloor data, including aids in using and understanding them, to the classroom. The investment in the next generation is key as they take on continued challenges of our planet.

DATA AVAILABILITY

Publicly available datasets were analyzed in this study. This data can be found here: http://nvs.nanoos.org.

AUTHOR CONTRIBUTIONS

JB conceived of this review and wrote the draft based on input from all authors. CR created **Figure 2**. All authors contributed to editing and improving the final manuscript.

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[15]https://www.shakealert.org/

[16]https://www.surfline.com

[17]https://oregon.surfrider.org/monitoring-ocean-acidification-in-oregons-marine-reserves/

oceanographic community in the PNW. The lead author and K. Juniper contributed to this paper while being members on the North Pacific Marine Science Organization's (PICES) Advisory Panel on North Pacific Coastal Ocean Observing Systems. This is contribution number 4875 from the NOAA Pacific Marine Environmental Laboratory.

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The Case for a Sustained Greenland Ice Sheet-Ocean Observing System (GrIOOS)

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Rapid mass loss from the Greenland Ice Sheet (GrIS) is affecting sea level and, through increased freshwater and sediment discharge, ocean circulation, sea-ice, biogeochemistry, and marine ecosystems around Greenland. Key to interpreting ongoing and projecting future ice loss, and its impact on the ocean, is understanding exchanges of heat, freshwater, and nutrients that occur at the GrIS marine margins. Processes governing these exchanges are not well understood because of limited observations from the regions where glaciers terminate into the ocean and the challenge of modeling the spatial and temporal scales involved. Thus, notwithstanding their importance, ice sheet/ocean exchanges are poorly represented or not accounted for in models used for projection studies. Widespread community consensus maintains that concurrent and long-term records of glaciological, oceanic, and atmospheric parameters at the ice sheet/ocean margins are key to addressing this knowledge gap by informing understanding, and constraining and validating models. Through a series of workshops and documents endorsed by the community-at-large, a framework for an international, collaborative, Greenland Ice sheet-Ocean Observing System (GrIOOS), that addresses the needs of society in relation to a changing GrIS, has been proposed. This system would consist of a set of ocean, glacier, and atmosphere essential variables to be collected at a number of diverse sites around Greenland for a minimum of two decades. Internationally agreed upon data protocols and data sharing policies would guarantee uniformity and availability of the information for the broader community. Its development, maintenance, and funding will require close international collaboration. Engagement of end-users, local people, and groups already active in these areas, as well as synergy with ongoing, related, or complementary networks will be key to its success and effectiveness.

Keywords: Greenland, ice sheet, ocean, observing system, glacier, atmosphere

INTRODUCTION

Scientific Rationale for a Greenland Ice Sheet-Ocean Observing System

Rapid mass loss from the Greenland Ice Sheet (GrIS) has raised interest in glacier–ocean interactions for three main reasons. First, melting at the marine margins of Greenland glaciers has emerged as a potential trigger of the observed dynamic ice loss (roughly half of the total ice loss) with important consequences for sea level rise. Second, increased freshwater discharge from the GrIS has the potential to impact global climate by affecting the Atlantic Meridional Overturning Circulation. Third, by altering nutrient fluxes, productivity, and biogeochemical properties of coastal waters, changes in freshwater discharge may impact marine ecosystems along the Greenland margin and potentially farther afield in the North Atlantic, with consequences for organisms using these regions as habitat and feeding grounds as well as societies relying on these ecosystems for subsistence.

Notwithstanding their importance, the exchanges of heat, freshwater, and nutrients that occur at the GrIS's marine margins are poorly understood and largely not accounted for in earth systems models used for projection studies that are part of the Climate Model Intercomparison Project and the Ice Sheet Modeling Intercomparison Project in support of the Intergovernmental Panel on Climate Change. This is largely due to the fact that exchanges between the GrIS and the surrounding ocean occur at the head of long, narrow, glacial fjords, at spatial scales inaccessible to earth systems models for the foreseeable future. Processes occurring at the ice sheet-ocean boundary include iceberg calving, sediment-laden turbulent upwelling plumes from surface meltwater discharge at depth (subglacial discharge), glacier submarine melting, fjord circulation, and strong katabatic winds. All of these processes are intrinsically challenging to observe and quantify because of their complexity and small spatial scales. On the glacier side, changes at the ice sheet-ocean boundary can trigger a dynamic response (i.e., stress perturbations in the ice sheet momentum balance) that results in thinning of the upstream glacier and further ice loss.

Considerable progress has been made over the last decade in understanding ice sheet-ocean exchanges of heat and freshwater in Greenland's glacial fjords. Yet challenges remain to understand the climatic controls on submarine melting, iceberg calving, the delivery of meltwater to the large-scale ocean, changes in nutrient availability, and the response of marine ecosystems. These knowledge gaps translate into an inability to appropriately represent these processes, even in parameterized form, in ice sheet, ocean, and climate models aimed at projection. Above all, there is widespread community consensus that progress requires concurrent and long-term records of glaciological, oceanic, and atmospheric parameters at the ice sheet-ocean margins – where the exchanges of heat, nutrients, and freshwater are occurring. Such observations are key to informing understanding, and constraining and validating models.

Tremendous efforts over the last decade have been devoted to pioneering measurements in glacial fjords and at glacier margins – challenging-to-access locations where no previous measurements existed and conventional observing techniques cannot be applied. These new measurements, and the model studies stimulated by them, have led to considerable advances in understanding ice sheet-ocean exchanges (Vieli and Nick, 2011; Straneo and Cenedese, 2015; Mortensen et al., 2018). These efforts, however, were not aimed at observing the entire system, including potential feedbacks and non-linearities, over extended periods of time. Here, following a series of workshops and documents endorsed by the community-at-large, we articulate the framework for an international, collaborative Greenland Ice sheet-Ocean Observing System (GrIOOS) that addresses the needs for society in the context of a changing GrIS.

Motivation

Rapidly increasing ice loss from the GrIS (Hanna et al., 2013; Velicogna et al., 2014; Bamber et al., 2018) has raised interest in the exchange of heat, freshwater, and nutrients between the GrIS and the subpolar North Atlantic, the Arctic, the Nordic Seas, and Baffin Bay, and their impact on marine ecosystems, for multiple reasons.

Sea Level Rise

Through rapid and sustained ice loss, the GrIS accounts for 25% of present day sea level rise, roughly twice that from Antarctica (Chambers et al., 2017; Dieng et al., 2017; WCRP Global Sea Level Budget Group, 2018). Ice loss occurs through changes in surface mass balance (ultimately inputting liquid freshwater to the ocean via surface and subglacial meltwater discharge) and in calving (inputting solid freshwater to the ocean). Changes in calving, in turn, can occur in response to oceanic and atmospheric variability (Holland et al., 2008; Hanna et al., 2009; Motyka et al., 2011; Straneo et al., 2013; Straneo and Heimbach, 2013). Recent increases in GrIS mass loss are primarily due to variations in surface mass balance, though solid ice discharge contributions have made up between ∼30% and ∼60% of total mass losses within recent decades (Enderlin et al., 2014; Van den Broeke et al., 2016). Increased iceberg calving and submarine melting have been identified as potential triggers for increased ice discharge (Motyka et al., 2011; Catania et al., 2018). Quantifying processes occurring at the ice-ocean interface thus becomes a high priority activity and prerequisite for projecting sea level rise from the GrIS.

Increased Freshwater Discharge Into the North Atlantic

A direct consequence of ice loss from the GrIS is the increase in the liquid (meltwater) and solid (iceberg) discharge of freshwater into the North Atlantic (Rignot et al., 2008; Bamber et al., 2012, 2018; Enderlin et al., 2016). This has raised concerns for the impact on the meridional overturning circulation, with potentially important climate consequences for society, based on past reconstructions and model projections (Böning et al., 2016; Yang et al., 2016; Thornalley et al., 2018). Our ability to project the impact of a shrinking GrIS on the large scale ocean circulation, however, is strongly dependent on the formulation of appropriate GrIS freshwater discharge boundary conditions in coupled ocean-atmosphere or ocean-only models. At present, the most up-to-date boundary conditions quantify the ice and meltwater discharge at the ice sheet-ocean margins, typically at the head of the narrow fjords, but neglect transformations within the fjords (Bamber et al., 2012, 2018). In contrast, observations and model studies of Greenland's fjords reveal a substantial modification of the freshwater discharge by in-fjord processes including iceberg melt, dilution of surface melt by turbulent plumes and, in general, a more complex fjord-ocean exchange of freshwater than that of a surface, freshwater export (Beaird et al., 2015, 2018; Enderlin et al., 2016; Jackson and Straneo, 2016; Moon et al., 2017; Mortensen et al., 2018). Understanding and appropriately formulating boundary conditions regarding freshwater flux is thus a key step in projecting the impact of the GrIS mass loss on the ocean.

Impact on Ocean Biogeochemistry and Marine Ecosystems

Interactions between the ocean and ice sheet fundamentally impact the biogeochemistry and structure of marine ecosystems in glacial fjords along the coast of Greenland. High rates of summertime primary productivity and phytoplankton biomass, coincident with nutrient enrichment of the upper water column downstream of marine-terminating glaciers, have been attributed to the sustained upwelling of deep, nutrient-rich ocean waters entrained as a result of subglacial discharge (Meire et al., 2017; Overeem et al., 2017; Hopwood et al., 2018; Kanna et al., 2018; Cape et al., 2019). This upwelling of nutrients is also thought to contribute to a lengthening of the growth season within glacial fjords, with secondary summer blooms accounting for an unusually large fraction of annual primary production (Juul-Pedersen et al., 2015). In contrast, no fjord-scale, positive fertilization effect is generally observed downstream of land-terminating glaciers, where glacial meltwater exported into surface waters primarily contributes to the strengthening of the pycnocline, exacerbating nutrient limitation (Meire et al., 2017). In addition to the carbon sink arising from high productivity in some fjords, the mixing of glacial melt with ambient ocean waters results in fjord waters that are significantly undersaturated in CO_2, suggesting that glacially influenced coastal waters constitute important CO_2 sinks along the Greenland margins (Rysgaard et al., 2012; Fransson et al., 2015; Meire et al., 2015). The correlation between the distribution of meltwater and timing of phytoplankton blooms on parts of the Greenland continental shelf further suggests that meltwater arrival may also be a factor in summertime bloom initiation beyond the confines of glacier-fjord systems (Arrigo et al., 2017; Oliver et al., 2018). However, large-scale impacts of freshwater export from the GrIS as a result of the potential export of glacially derived iron to iron-limited regions of the North Atlantic, remain poorly constrained owing to a limited understanding of the fate of glacially modified waters and their nutrients beyond the confines of Greenland's fjords.

Like other Arctic and sub-Arctic glacial systems, Greenland glacial fjords are hotspots of secondary productivity, characterized by rich marine ecosystems featuring high densities of seabirds, marine mammals, and fishes (Lydersen et al., 2014; O'Neel et al., 2015; Laidre et al., 2016; Meire et al., 2017). They serve as important sites for traditional hunting, subsistence, and commercial fisheries (Meire et al., 2017), contributing significantly to the regional economy (Berthelsen, 2014). In addition to sustaining high productivity, processes occurring at the ice sheet-ocean interface may aggregate plankton or stun plankton via freshwater osmotic shock (Lydersen et al., 2014), making them easy prey for larger surface-feeding predators and multiple trophic levels. In general, the glacier ice mélange, a heterogeneous mixture of calved glacial ice and sea ice that can freeze solid, is a primary habitat for Arctic marine mammals in glacial fjords. In winter and spring, this solid area produces a heterogeneous habitat for ringed seals (*Pusa hispida*), bearded seals (*Erignathus barbatus*), polar bears (*Ursus maritimus*), numerous sea birds, and land mammals such as Arctic fox (*Vulpes lagopus*) (Laidre et al., 2018a,b). Other species that are ice-associated, such as the narwhal (*Monodon monoceros*), forage at the glacier front and among the mélange to utilize the productive waters during summer (Laidre et al., 2016). In some areas of the Arctic where the permanent multi-year sea ice has vanished in recent years, glacial fjords are replacing sea ice habitat for ice-breeding species that require stable ice for reproduction (Lydersen et al., 2014).

Ongoing changes at the ice sheet-ocean margins, including increasing freshwater discharge into coastal fjords, have led to questions regarding how these changes will impact carbon cycling, whether changes in the physical habitat may impact populations that rely on glacial fjords for habitat, refuge, and subsistence, and what the consequences will be for the patterns and timing of biological productivity – which may have cascading effects up the food chain. Thus, understanding the influence of ice loss on biological systems, including fisheries, is a major thrust of Greenland ice sheet-ocean exchange research.

Outlet Glaciers and Glacial Fjords

Unraveling the variability of processes occurring at outlet glacier marine margins and in glacial fjords is essential to make progress on the overarching questions pertaining to drivers of mass loss from the GrIS and their impact on the ocean circulation, its biogeochemistry and its ecosystems. Glacial fjords represent the bottleneck through which oceanic heat is delivered to the ice sheet margins, and through which meltwater, icebergs, and nutrients

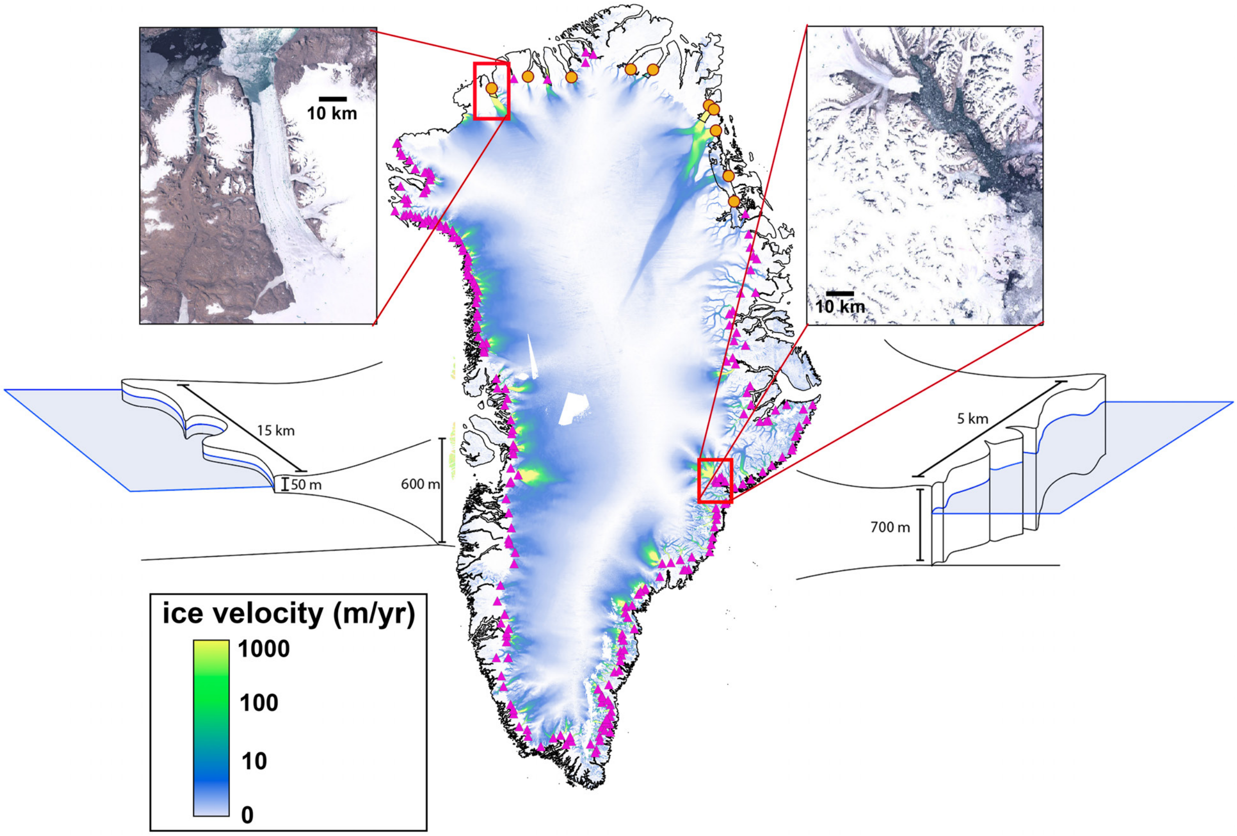

FIGURE 1 | The exchange of heat and freshwater between the ocean and the Greenland Ice Sheet occurs at the margins of over 200 marine terminating glaciers, visible as narrow areas of increased ice flow, distributed around the perimeter of Greenland that discharge into narrow, long and deep fjords. Several of these glaciers are characterized by long (>5 km) floating ice tongues (left inserts, orange circles) but most glaciers have lost their long floating regions (right inserts, pink triangles). Glaciers identified as having long floating ice tongues greater than 5 km in length, are determined through their height above floatation. Height above flotation is calculated using surface elevation data from the GIMP DEM (Howat et al., 2017) and ice bottom from BedMachine 3 (Morlighem et al., 2017). The background ice velocity is from a 2015–2016 mosaic (Joughin et al., 2017); glacier locations are from Rignot and Mouginot (2012).

(e.g., silica, iron, phosphorus) are exported into the global ocean (**Figure 1**). These glacial fjords are typically ∼100 km long and 5–10 km wide. Outlet glaciers in Greenland are often grounded in hundreds of meters of water. Only a handful of fjords in Northern Greenland have a floating ice tongue (**Figure 1**, left insets) that covers much of the fjord's extent (Wilson et al., 2017). Fjord topography, including the presence of a sill, regulates the exchange of water masses with the continental shelf, where both waters of Atlantic and Arctic origin coexist (Gladish et al., 2015; Carroll et al., 2017). Fjords with sills deeper than ∼100 m are characterized by a warm, Atlantic-sourced layer underneath a colder, fresher surface layer (Murray et al., 2010; Straneo et al., 2012; Inall et al., 2014; Mortensen et al., 2014).

Key processes that govern the exchanges of heat, freshwater, and nutrients at the ice/ocean boundary, and the upwelling of deep nutrient-rich ocean waters at the glaciers' margins, include localized plume upwelling driven by the subglacial discharge of ice sheet surface melt at glacier grounding lines (Jenkins, 2011; Xu et al., 2012; Sciascia et al., 2013; Kimura et al., 2014; Carroll et al., 2015; Cowton et al., 2015; Slater et al., 2015) and distributed melting along the glacier face (**Figure 2**). The circulation of waters in the fjord is thought to be regulated by a combination of buoyancy (Motyka et al., 2003), shelf-driven (Jackson et al., 2014; Fraser and Inall, 2018), and wind-driven forcings (e.g., Moffat, 2014; Spall et al., 2017). This circulation guarantees a continuous supply of heat to melt ice (see review by Straneo and Cenedese, 2015) and regulates the export of the strongly diluted meltwater (Beaird et al., 2015, 2017; Jackson and Straneo, 2016). Icebergs, commonly found next to calving glaciers, release meltwater throughout much of the fjord water column as they melt (Enderlin et al., 2014; Moon et al., 2017).

Subglacial discharge, i.e., ice sheet surface melt routed to the ice sheet base via the englacial drainage system (Noël et al., 2016; Van den Broeke et al., 2016; Langen et al., 2017; Wilton et al., 2017), has emerged as a major player in ice sheet-ocean interactions, since it amplifies ice sheet-ocean exchanges (e.g., Jenkins, 2011; Slater et al., 2015). Calving of icebergs, which balances most of the ice flux across the grounding line, is a poorly understood process that is likely influenced by climatic conditions and is a key regulator of glacier dynamics (Schoof et al., 2017). Efforts to extend the temporal record of ice sheet mass loss is the subject of considerable research (e.g., the

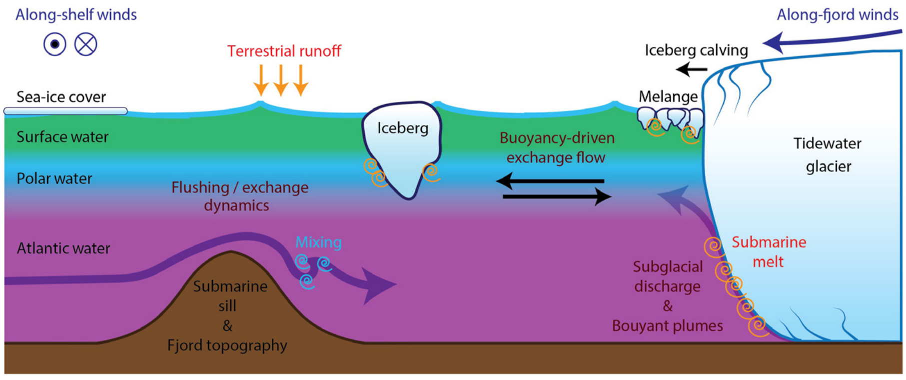

FIGURE 2 | Schematic of a Greenland glacier/fjord system showing relevant physical processes that govern circulation in the fjord and at the glacier-fjord boundary, typical stratification and water masses, and sources of freshwater to the fjord.

ongoing East GRIP Ice-Core Project focusing on the Northeast Greenland Ice Stream).

Building a Case for GrIOOS: The Last Decade

The rapid increase in mass loss from the GrIS began in the early 2000s (Krabill et al., 2004; Rignot et al., 2008; Murray et al., 2015; Catania et al., 2018; Wood et al., 2018) and it was only a decade later that the importance of processes at the ice sheet-ocean margins became apparent, making ice sheet-ocean interactions in Greenland and globally a novel and rapidly growing area of research. Key to community progress have been a series of workshops, and related follow-up documents, that sought for the first time to bring together the diverse disciplines needed to advance the science.

The first of these workshops, a multi-disciplinary International Workshop on "Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing," was organized by the US Climate and Ocean Variability, Predictability, and Change (US CLIVAR) Working Group on Greenland Ice Sheet-Ocean interactions in June 2013. It brought together over 100 international scientists and program managers with the goals to summarize the current state of knowledge and questions (Straneo et al., 2013) and to develop several key recommendations to make progress (Heimbach et al., 2014). One major recommendation was the collection of long-term time series (both *in situ* and remotely sensed) of critical glaciological, oceanographic, and atmospheric variables at key locations in and around Greenland through the establishment of GrIOOS. The research community recognized that such measurements are needed to provide information on the time-evolving relationships between climate forcing, ice sheet dynamics, and ocean characteristics. The lack of such data has hindered our ability to explain and model the complex interactions among ice-ocean-climate, leaving major gaps in our ability to project future changes. The community noted that GrIOOS data would be critical, not only to validate hypotheses, but also to provide boundary conditions, forcings, and a point of comparison for both ocean and ice sheet model simulations.

Following the recommendations made in the 2014 report, the Study of Environmental Arctic Change Land Ice Action Team, in collaboration with the Greenland Ice Sheet Ocean Interaction Science Network (GRISO), and the Climate and Cryosphere Project (CliC) of the World Climate Research Program, organized a workshop to make progress on the design and implementation of GrIOOS. The resulting 2015 workshop was attended by 47 participants from seven countries, including U.S. agency program managers (National Science Foundation, NSF, and National Aeronautics and Space Administration, NASA) and a representative of the Greenland government. Participant expertise included oceanography, glaciology, climate and ice sheet modeling, marine ecosystems, and paleoclimatology. Together, this group examined questions such as: (i) What are the essential ice sheet and ocean variables? What measurements and observing systems already exist? (ii) What should be the structure of the GrIOOS system regarding target observing sites and optimal instrumentation? (iii) How could data be collected, quality controlled, and distributed? Tentative answers to these questions are summarized in Straneo et al. (2018) and have informed the GrIOOS system design discussed here.

Societal Benefits From GrIOOS

Our inability to quantify GrIS-ocean exchanges, and their climate forcing, is a major scientific obstacle to understanding causal origins of past variability and to predicting the future of GrIS and its impact on the neighboring ocean regions, including the marine ecosystems. Connecting science across disciplines and countries, which is necessary to address key climate-related questions, has proven challenging because there is no integrating framework for a comprehensive ice sheet and ocean observing system, including needed structures for data management and dissemination, translating observations to usable model data and parameterizations, and overall cyberinfrastructure to support FAIR (Findable, Accessible, Interoperable, Re-usable) data.

The objectives of GrIOOS are to address all of these challenges by determining essential observations ('Essential Variables') for the ice sheet-ocean-atmosphere system, establishing guidelines for instrumentation that can be used across institutions and nations, creating metadata standards, establishing quality control best practices, and developing a user-friendly platform for FAIR data archiving, access and analysis. Fundamentally, these objectives support overarching goals to understand and project Greenland (and Arctic) ice sheet-ocean interactions and their impact on the ocean, including sea level rise. They explicitly contribute to two of the grand challenges issued to the international scientific community by the World Climate Research Programme and its subsidiaries, such as CLIVAR and CliC: (1) Melting ice and global consequences; (2) Regional sea-level change and coastal impacts.

GrIOOS will also serve other critical societal needs. Greenlandic communities rely on information about fjords, icebergs, and sea ice conditions for hunting and travel. Most of this information is based on personal experience and shared by word of mouth or social media. For coastal navigation and shipping, the ice service at the Danish Meteorological Institute (DMI) has a long history of mapping sea ice and icebergs hazards, especially around southern Greenland, for navigation purposes. The ice service is now automated and generates bi-weekly maps, taking advantage of Sentinel satellite imagery to give an overview of sea ice extent and iceberg distribution. With a GrIOOS program in place, we can create improved products that provide higher spatial resolution and, depending on the observation type, better temporal resolution. Such a program can also provide datasets that are requested by local hunters, fishers, policy makers, and business owners. Through coordination with colleagues at Asiaq Greenland Survey, this new or improved data can be shared with local communities in an easily usable, near-real time format, such as through an established GrIOOS data portal, or through appropriate media available to these communities. Asiaq also maintains an interactive Geographical Information System (GIS) website that is heavily used by the local community[1], which could provide an additional platform for data integration and access. The Government of Greenland has prioritized "strengthening the population's knowledge of climate change" and "disseminating information about climate change" as two of its four main research goals (GCRC, 2015). GrIOOS observations and cyberinfrastructure can support these goals.

International collaboration is also essential for regional engagement in the integration of science and traditional knowledge in ice sheet-marine coupling research. The Pikialasorsuaq partnership is a new collaboration between Greenland, Denmark, and Canada. The Pikialasorsuaq is the Inuit name for the North Open Water Polynya. This polynya is particularly important as a shared resource between Canada and Greenland, affecting biogeochemical processes at the northern limit of Baffin Bay (Barber and Massom, 2007). The governments of Canada, Greenland, and Denmark are currently discussing how to manage the Pikialasorsuaq region as an international shared resource. Based on the concept of a larger Baffin Bay Observing System (Rysgaard and BBOS Committee, 2017), the GrIOOS system will include an effort to bring traditional knowledge from communities surrounding the North Open Water polynya into the ice sheet-ocean observing system framework.

[1]www.nunagis.gl

VISION FOR A GREENLAND ICE SHEET-OCEAN OBSERVING SYSTEM

The overarching vision for GrIOOS is the simultaneous observation of glaciological, oceanic, and atmospheric 'essential variables' (both *in situ* and remotely sensed) at ice sheet-ocean sites around Greenland, to be sustained over the coming decades. The observation should be sustained over multiple cycles of dominant atmospheric and oceanic modes of variability (e.g., National Academies of Sciences et al., 2016), in particular the North Atlantic Oscillation, Greenland Blocking, Atlantic Multidecadal Variability, and Pacific Decadal Variability. It should also cover the era of continuous satellite observations of several essential variables, which will be integrated with the *in situ* GrIOOS system and data.

The ensemble of GrIOOS sites should cover a range of ice sheet-ocean configurations, connect to all major oceanic basins around Greenland, be representative of the different climatic regimes, and capture systems thought to be dominant contributors to GrIS mass loss. The minimum set of essential variables to be collected at each site is motivated by present-day understanding of the key oceanic, glaciological, and atmospheric variables behind the processes that govern ice sheet-ocean exchanges of heat, freshwater, and nutrients. Additional inputs for any GrIOOS site are bathymetry and bed elevation. We refer to these as foundational datasets, which are critical but only need to be collected once. Ancillary measurements at a site, such as sediment cores that provide context for GrIOOS observations to be extended back in time, e.g., via paleo-proxy reconstructions (e.g., Andresen et al., 2012; Henry et al., 2016), or seismic and geodetic stations that connect GrIOOS to other scientific communities, are also highly desirable (e.g., Nettles and Ekström, 2010; Bevis et al., 2012).

The development and maintenance of GrIOOS will require close international collaboration. GrIOOS implementation will need to be coordinated amongst different countries, paying close attention to minimizing costs and optimizing shared logistics. Data processing protocols and data sharing practices must be identified, shared, and maintained. Quick, open, and centralized access to data is vital. Below we explain in detail the proposed GrIOOS framework.

In developing GrIOOS, we seek to follow the Framework for Ocean Observing (Task Team for an Integrated Framework for Sustained Ocean Observing, 2012) in an extended form that captures both the fundamentally multi-disciplinary nature of the ice sheet-ocean system, and the detail required to advance process level understanding.

Identifying the Essential Variables of a GrIOOS Site

Several key constraints are taken into consideration in identifying the ensemble of essential variables gathered at each GrIOOS site. First the ensemble of these variables should be sufficient input

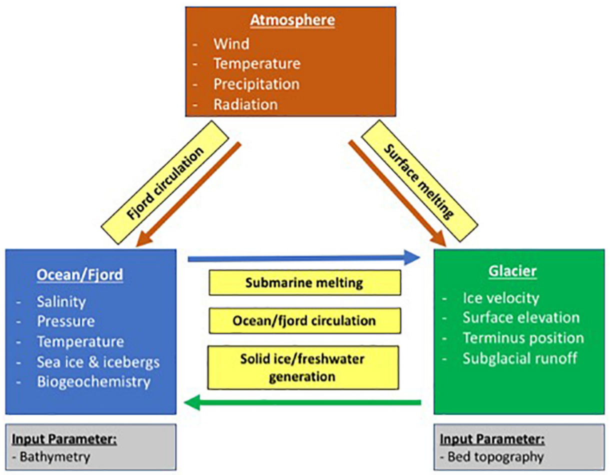

FIGURE 3 | Identified essential variables and their interconnection (inside boxes) at a GrIOOS site.

to algorithms or models that describe variations in the ice sheet-ocean processes that are relevant to addressing the questions identified above (**Figure 3**). Second, the essential variables should be practical to obtain, i.e., measurable and sustainable in terms of cost or derivation. Third, these variables should be relatively easy to relate to the larger scale oceanic, glaciological, and atmospheric context. Here, we summarize the relevant processes within the three focus areas identified above and identify essential variables that can represent their variability.

Sea Level Rise

Future sea level rise from the GrIS depends on mass loss through surface melt and through solid ice discharge of icebergs at the ice sheet-ocean boundary. Improving understanding of ice sheet-ocean interactions will inform research on the location and magnitude of ice sheet variability due to atmospheric and oceanic changes. To examine the ice sheet-ocean-atmosphere system, we have identified: ice sheet surface velocity; ice sheet surface elevation (and ice thickness via bed topography data); terminus position; surface runoff and subglacial discharge as the minimum set of essential variables (**Table 1**).

Ice sheet surface velocity, combined with ice thickness and grounding line information, can be used to calculate ice flux at marine termini around Greenland (e.g., Rignot et al., 2011; Enderlin et al., 2014). Time-series of these variables are also essential in unraveling the processes governing flow variability (e.g., Stearns and van der Veen, 2018). Acceleration, thinning, and retreat often occur near-coincidentally, driven by processes at the ice-bed and ice-ocean interface that are impossible to observe directly.

Frontal ablation at the ice-ocean interface, which includes submarine melting and iceberg calving, all influence ice sheet behavior and ice loss (Straneo et al., 2013; Kjeldsen et al., 2017). Submarine melting is largely thought to be controlled by the thermal forcing of the ocean waters reaching the glacier (**Figure 2**), and is amplified by large ocean velocities, such as those due to subglacial discharge driven turbulent, upwelling plumes at the glaciers' margins during the melt season (Mortensen et al., 2013; Bendtsen et al., 2015; Mankoff et al., 2016; Jackson et al., 2017). Calving is accelerated in regions undercut via submarine melting (described above; Bartholomaus et al., 2013; Chauché et al., 2014; Fried et al., 2015), but can also occur when the terminus reaches flotation and basal crevasse propagation leads to full-thickness calving (James et al., 2014; Murray et al., 2015). Essential observations needed to constrain submarine melting: are subglacial discharge, and ocean temperature and salinity as a function of pressure (**Table 1**), The essential observations of terminus position and ice velocity, combined with calculations of submarine melt will inform research on calving processes, ice sheet response to ocean change, and, ultimately, sea level rise.

Freshwater Export

Glaciers release freshwater at the ice sheet-ocean margins as solid ice (icebergs) and meltwater. Meltwater enters the fjords as surface runoff, submarine melt across the termini, or subglacial discharge (**Figure 2**). Icebergs undergo considerable melting as they transit through the fjords, giving rise to an additional meltwater flux (distributed along the iceberg depth) and a residual iceberg export at the fjord's mouth. This melting, in turn, is largely controlled by the fjord circulation and temperature structure. The export is controlled by local winds, the fjord circulation and fjord bathymetry.

Meltwater released at depth along the glacier face (submarine melt and subglacial discharge) creates plumes that rise, entrain large volumes of deep fjord waters, and produce a much greater transport than the volume of meltwater released (e.g., Motyka et al., 2003; Beaird et al., 2018). While the details of the processes controlling the dilution and export of the meltwater and of icebergs, from the glacier and fjord, are complex, they are thought to be largely controlled by: (1) the release of subglacial discharge and surface runoff; (2) the iceberg flux; (3) the temperature of the fjord waters; (4) the fjord circulation; (5) local winds. These in turn, can be described in terms of the surface mass balance components, the calving flux, properties inside the fjord and on the nearby shelf (since this gradient controls the fjord/shelf exchange), local and regional winds. Note that while it would be highly desirable to include fjord velocities (or circulation) as an essential variable, these measurements are costly and largely uncertain due to the high spatial and temporal variability of velocities in these narrow fjords (Mortensen et al., 2014; Jackson and Straneo, 2016; Boone et al., 2017). Information about iceberg distribution and sea ice coverage is also critical for classifying ice hazards, which is a crucial metric for shipping, industrial development, and local community activities in the marine areas surrounding Greenland (e.g., Barber et al., 2014).

Impact on Biogeochemistry and Ecosystems

The timing, mode of delivery, properties, and magnitude of freshwater export into the ocean fundamentally shape ocean biogeochemistry. Plumes of meltwater and entrained ocean waters rising at the glacial margin drive a vertical transport of dissolved nutrients and sediments toward the surface

TABLE 1 | GrIOOS essential variables, with information about readiness levels for component requirements, observation instruments and methods, and data and information systems.

Component	Essential Variable	Requirements	Observations	Data and Information
Ocean: *hydrography*	Temperature	Mature	Concept*	Mature
	Salinity	Mature	Concept*	Mature
	Irradiance	Mature	Concept*	Mature
	Chl-a fluorescence	Mature	Concept*	Mature
Ocean: *biogeochemical*	Dissolved Oxygen	Mature	Concept*	Mature
	Turbidity	Mature	Concept*	Mature
	Nitrate	Mature	Concept*	Mature
	pCO_2 and pH	Mature	Concept*	Mature
	Iceberg production	Pilot	Concept	Concept
Ocean: *ice-related*	Iceberg distribution	Pilot	Concept	Concept
	Sea ice concentration	Pilot	Concept	Concept
	Surface velocity	Mature	Mature	Mature
	Terminus position	Mature	Concept	Concept
Ice	Surface elevation	Mature	Mature	Mature
	Surface runoff	Mature	Mature	Mature
	Subglacial discharge	Mature	Concept	Mature
	Temperature	Mature	Mature	Mature
Atmospheric	Wind	Mature	Mature	Mature
	Precipitation	Mature	Mature	Mature
	Radiation	Mature	Mature	Mature

The readiness levels, moving from concept to pilot to mature, are based on terminology for the Framework for Ocean Observing (see ***Figure 8*** *in Task Team for an Integrated Framework for Sustained Ocean Observing, 2012), with different requirements for each category: requirements, observations, and data and information.* *Locational challenges add to 'concept' classification.*

ocean, where they can impact the growth of phytoplankton by respectively fueling primary production or altering light penetration and optical properties. Measurements of nitrate, a primary limiting nutrient present in low concentration in meltwater but abundant in the deep ocean, alongside turbidity, in this way serve as essential tracers for ice-ocean exchanges and glacier-driven circulation, as well as nutrient availability. The response of phytoplankton to glacial modification of upper water column physical and chemical properties can in turn be examined through measurement of chlorophyll-a fluorescence and dissolved oxygen. Alongside measurements of ambient light, these parameters can, in concert, give insight into primary productivity rates and the biomass of organic carbon available to higher trophic levels, important ecosystem properties. The integrated response of the carbon cycle to ice-ocean exchanges, including the overall magnitude and sign of the atmosphere-ocean carbon flux, is a function of both biological cycling and thermodynamic effects stemming from physical mixing of glacial and ocean water masses (Meire et al., 2015). Time series of pCO_2 and pH, alongside biological parameters previously described, are therefore essential variables to constrain carbon cycle response (**Figure 3**).

The Relevant Essential Variables

Based on a summary of the processes and major controlling variables outlined above, and in consideration of both feasibility and reliability of existing technologies for long-term measurement, we suggest the following essential oceanic, glaciological, and atmospheric variables for each GrIOOS site (**Table 1**):

- Oceanic variables include temperature and salinity as a function of pressure both within the fjord and across the nearby shelf. Sea ice cover, iceberg production, and iceberg distribution are also essential. Biogeochemical variables needed to characterized productivity include downwelling irradiance, chlorophyll-a fluorescence, and dissolved oxygen. Turbidity and nitrate are needed to quantify seasonality in nutrient availability associated with glacial discharge and fjord circulation. Finally, pCO_2 and pH are needed to constrain the carbon cycle response. Tracking of properties both inside the fjord and on the nearby shelf is needed to separate remote and local drivers of variability.
- Glaciological variables include ice velocity, surface elevation, ice thickness (via bed and surface elevation), terminus position, surface melt (i.e., that generates surface runoff) and subglacial discharge. These variables will allow us to calculate iceberg calving rates, ice volume changes, and freshwater discharge at the GrIS marine margin.
- Atmospheric variables include local weather data (winds, air temperature, precipitation, radiation, etc.) to provide information essential to estimating the regional and fjord-scale atmospheric forcing of the ice sheet and ocean surface.
- Additional foundational datasets critical for any GrIOOS site are bedrock and ocean bathymetry.

FIGURE 4 | Example of potential instrumentation for a GrIOOS site located at the margins of a tidewater glacier (note: not to scale).

How to Get the Essential Variables for Each GrIOOS Site

It is envisioned that the essential variables described above (and in **Table 1**) will be gathered at each site either as *in situ* measurements or as derived quantities from, for example, remote sensing. A generic GrIOOS site is depicted in **Figure 4**. For all essential variables, there is a strong need for year-round observations. High temporal resolution (as often as hourly to weekly depending on variable) measurements are required since it is unclear which timescales govern both the oceanic forcing and the glacier response, or whether threshold behavior exists that only bears out during certain environmental conditions. Engagement with communities located near GrIOOS sites will be a key part to the temporal sampling required.

Ocean

Ocean essential variables require year-round measurements both in the glacier vicinity (typically in the fjord) and on the nearby continental shelf. Depending on the fjord/glacier type, the way these measurements are achieved may differ substantially. Floating ice shelves (or 'floating tongues') offer the possibility of suspending instruments from the ice through bore holes that are expensive to drill but provide ideal platforms. Tidewater glaciers with substantial calving are challenging because of the deep draft icebergs and general inaccessibility of the region. These require site specific strategies that may include subsurface moorings (**Figure 4**). Sensors deployed on marine mammals may be appropriate for some sites where other technologies are deemed impractical. Biogeochemical sensors present additional challenges that will also necessitate site-specific strategies. A subset of biogeochemical sensors (e.g., fluorescence, O_2, pCO_2, pH) need to be deployed in the upper 10–50 m of the water column where major biological processes and freshwater export take place. By contrast, sensors used to characterize links between physical processes and chemical properties of the ocean (e.g., nutrient fluxes and distributions) may in certain cases be deployed subsurface.

The size and distribution of icebergs in fjords and the surrounding ocean are important to characterize for their impact on freshwater- and nutrients dynamics. New efforts to quantify iceberg distributions are now possible given the robust temporal coverage of both optical and radar satellite imagery over the Arctic. Ocean nodes should integrate remote sensing results of both iceberg distribution and sea ice coverage, which are essential for freshwater flux calculations (Moon et al., 2017; Sulak et al., 2017). Iceberg detection from Sentinel satellites around Greenland has been automated by the DMI and daily plots for several distinct locations are displayed on the Danish public outreach website polarportal.dk, based on the methods of Buus-Hinkler et al. (2014) but at finer spatial resolution of 40 and 10 m. While this technique is able to distinguish icebergs at unprecedented resolution, it shares, with other remote sensing data products, the disadvantages of limited temporal and spatial coverage and is not capable of distinguish icebergs trapped within sea ice or mélange in front of calving outlet glaciers. Finally, it is notable that despite the large fraction of discharge from the GrIS occurring as solid ice, little information is available concerning how icebergs affect nutrient cycling within Greenland's fjords, making iceberg observations also critical for ocean biogeochemistry.

Glacier

Most glacier essential variables (ice surface velocity, terminus position, ice sheet surface elevation) can be acquired via remote sensing sensors already in orbit and mature analysis techniques. Some variables can already be acquired from consistently archived and served data streams and will not require significant GrIOOS investment. For example, both optical and radar satellites now allow weekly to monthly measurements of ice surface velocity, which is systematically processed and served through U.S. and European data archives. Some datasets, however, require further GrIOOS science and research development. In particular, terminus position is not currently provided in a systematic way, largely consisting of sporadic terminus shapefiles available from individual investigators. Existing networks and data sets to support development of glacier and ice sheet essential variables are discussed in Section "Glacier and Ice Sheet." Additional *in situ* observations of the outlet glacier system could also take advantage of ocean deployments for additional sensors to improve understanding with satellite-based observations and time-lapse cameras to provide high temporal and spatial information (**Figure 4**). The best current source for surface mass balance information are regional climate models (see Dynamical and Statistical Reconstructions). We envision essential variables will be linked on a website that would bring together the disparate data sets for the general purpose of quantifying the spatio-temporal variability in glacier behavior (see Data Protocol and Management).

Atmosphere

The atmosphere node provides variables that support both glacier and fjord measurements. At the local scale measurements are obtained via Automated Weather Stations (AWS; **Figure 4**). AWS deployed at locations adjacent to the glacier terminus can provide essential variables (air temperature, winds, precipitation, radiation) and other standard meteorological observations (**Table 1**). These data can also improve remote sensing and reanalysis products. Depending on the location, such measurements may be available through several of the existing meteorological station networks, e.g., DMI, see Weather Station Data). At the regional scale, estimates of air temperature, winds, pressure, and other meteorological parameters are available through regional climate model or global atmospheric analysis, forecast or reanalysis products (see Dynamical and Statistical Reconstructions). These data will fulfill many of the variable needs for capturing regional-scale atmospheric conditions over the glacier-fjord-continental shelf system. In addition, large-scale circulation indices, such as the Greenland Blocking Index (Hanna et al., 2016, 2018), will be helpful for contextualizing ice sheet-atmosphere-ocean interactions.

Foundational Datasets: Bathymetry and Bed Elevation

Ice sheet bedrock topography and fjord bathymetry are critical foundational datasets. Significant efforts have been made over the last decade to improve estimates of ice sheet bed elevation, particularly beneath the outlet glaciers of the GrIS, with airborne ice-penetrating radar (Leuschen et al., 2018). In addition, new bathymetric and airborne gravity surveys within multiple glacier fjords in Greenland have been made over the last few years as interest in ice sheet-ocean interactions has increased (e.g., Fenty et al., 2016; Rignot et al., 2016; Kjeldsen et al., 2017; Millan et al., 2018). These provide an even more detailed picture of the topography beneath glacier termini and within the fjord. Together, these types of observations have been used to construct a seamless bed elevation product across the GrIS ice sheet-ocean margin using a mass-conservation approach that provides a best estimate for the bed topography constrained by observational data (Morlighem et al., 2011, 2017). Since these new data use both ice-penetrating radar and bathymetric data, grounding line depth estimates have improved dramatically over previous estimates and provide a more accurate picture of the geometric setting for critical outlet glaciers terminus regions. Even with these improvements, many outlet glaciers (adjacent) within the GrIS have not been surveyed with ice penetrating radar (bathymetric mapping) and are poorly constrained in the mass-conservation inversion. Any additional bedrock/bathymetric data collected as part of GrIOOS should therefore be readily made available to improve the existing database.

Characteristics of GrIOOS Sites

The ensemble of GrIOOS sites should span a range of geometries that take into account the glacier/fjord depths, fjords with and without sills, glaciers with and without floating termini, and different oceanic basins. Choice of the sites should take into account existing measurements, noting sites that are already being monitored that could become GrIOOS sites with minimum additional measurements. Proximity of other observing networks (see below) to sites can optimize sustainability, provide broader context, and allow shared logistics costs. Sites close to inhabited or regularly serviced centers allows for accessibility at reduced costs and may be a source of information to the local community. There should be a focus on the largest contributors to Greenland Ice Sheet mass loss, and the proximity of paleo records should also be taken into account.

At the initial GrIOOS development meeting, several possible observational sites were suggested based on voting of each participants' top three sites and the considerations described above, such as existence of ongoing observations, logistical support, scientific rationale, and societal rationale. The glacier/fjord sites with the most votes were Helheim Glacier/Sermilik Fjord, 79 N/NE Greenland Ice Stream (NEGIS), and Jakobshavn Isbrae/Ilullisat Icefjord, with additional priority sites listed here in order of voting (**Table 2**). The top three sites are dominated by glaciers that calve via full-thickness events and where melt-induced terminus change may play a reduced role (Fried et al., 2018). In a fully implemented GrIOOS, care should be taken to include a broad range of glacier settings, defined by the glacier dynamic behavior, and fjord settings, defined by geometry and proximity to distinct open ocean regions.

Additionally, during the previous GrIOOS workshop, participants helped to identify and discuss lessons learned from other ongoing observational programs, such as the Geological Survey of Denmark and Greenland (GEUS) Program for Monitoring of the Greenland Ice Sheet (PROMICE), or

TABLE 2 | Characteristics of potential GrIOOS glacier-fjord sites, including the ocean basin adjacent to link to existing open ocean measurements, the fjord and glacier geometry to ensure a diversity of glacier/fjord types, Greenland sector, and whether *in situ* measurements of ocean (O), ice (I), atmosphere (A), and ecosystem (E) variables exist now or in the past.

Fjord/Glacier System (Figure 5 label)	Greenland Sector	Adjacent Ocean Basin	Max Fjord Depth (m)	Sill depth (m)	Grounding line depth (m)	Ice flux (km^3/year)	Existing *in situ* observation
Sermilik Fjord/Helheim Gl. (HG)	Southeast	Irminger Sea	920	N/A	700	16	O,I,A,E
NEGIS[a]/79N (NEGIS)	Northeast	Fram Strait	800	200	600	9	O
Ilulissat Icefjord/Jakobshavn Isbrae (JI)	Central West	Labrador Sea	800	250	1000	21	O,I,A
Petermann Glacier[a]/Fjord (PG)	North/Northwest	Nares Strait	810	440	610	6	O,I,A
Rink Isbrae/Karrats Isfjord (RI)	Central West	Labrador Sea/Davis Strait	1200	430	840	9	O[b]
Kangerlug- ssuaq Glacier/Fjord (KG)	Southeast	Irminger Sea/Denmark Strait	880	N/A	700	13	O[b]
Upernavik[c] Glacier/Fjord (UG)	Northwest	Baffin Bay	900	N/A	100–700	2–4	I,A
Bowdoin Glacier/Fjord (BG)	Northwest	Baffin Bay	600	200	250	0.5	O,I,A
Kangiata Nunaata Sermia/Godthabsfjord (KNS)	Southwest	Labrador Sea	600	200	250	7.5	O,I,A,E

The listed order represents the number of votes obtained for developing each glacier/fjord system as a GrIOOS site (see text). [a]*The Northeast Greenland Ice Stream/79 N and Petermann Glacier both terminate in perennial floating ice tongues.* [b]*Time-series of ocean variables exist here, but only for limited time ranges in the past and not at present.* [c]*Ranges are given since four glaciers flow into Upernavik Fjord (Ahlstrøm et al., 2013).*

through the Global Ocean Observing System Framework for Ocean Observing (Task Team for an Integrated Framework for Sustained Ocean Observing, 2012). Several potential key requirements were identified:

- Light and sustainable: Logistically or instrumentally expensive observing systems are difficult to maintain over time. Simple logistics, and ones that would make use of interested communities, are best. However, previous efforts [e.g., US Geological Survey (USGS) monitoring for mountain glaciers] have shown that it is best to aim for oversampling during the first several years of the observing system, with the objective to identify key sites for sustained observations, accommodating potential needs to scale down the observing system over time.
- Monitoring requires proven technology: Although testing new technology is an interesting prospect if it can reduce later costs, an observing system is not the best place to implement new technologies.
- Build on available logistics and programs: Although programs that are already running would not easily scale up, they can provide logistical support for additional instrumentation deployment, if necessary.

EXISTING NETWORKS

Interest in the GrIS and surrounding fjords and ocean has grown rapidly over the last few decades and led to an expansion of monitoring networks both *in situ* and from remote sensing observations (**Figure 5**). GrIOOS will be developed to connect with and leverage these existing networks. In particular, the connection with regional programs will provide the needed 'far-field' connection of GrIOOS' sites to the ocean (continental shelf and large scale ocean); the ice sheet and the atmosphere. Here, we outline a number of these existing research and observation activities (see **Figure 5** for location).

Ocean

Moored Arrays

The mooring array in Fram Strait (de Steur et al., 2014) to measure Arctic Outflow was deployed in 1997 as a government funded monitoring system collaboration between Norwegian Polar Institute (Norway) and the Alfred Wegener Institute (Germany). The array records temperature, salinity, currents, ice thickness and ice drift, and is complemented by annual conductivity/temperature/depth (CTD), lowered acoustic Doppler current profiler (LADCP) and tracer transects in August and September (**Figure 5**). It is expected that it will be maintained for at least another decade. The array is concentrated in deeper water and lacks moorings on the Greenlandic continental shelf (due to ice hazards), however, repeat CTD transects are conducted on the shelf whenever possible.

A mooring array across Davis Strait was deployed in 2004 as a US-Canadian collaborative project to measure Arctic outflow west of Greenland (Curry et al., 2014). The mooring array spans across the continental shelves (**Figure 5**) and measures velocity, temperature, salinity, sea ice thickness. It is supplemented by marine mammal acoustics, year-round glider observations, and annual or biennial hydrographic sections. Hydrographic measurements also include macro-nutrient concentrations (i.e., nitrite plus nitrate, silicate, phosphate, ammonium) and oxygen

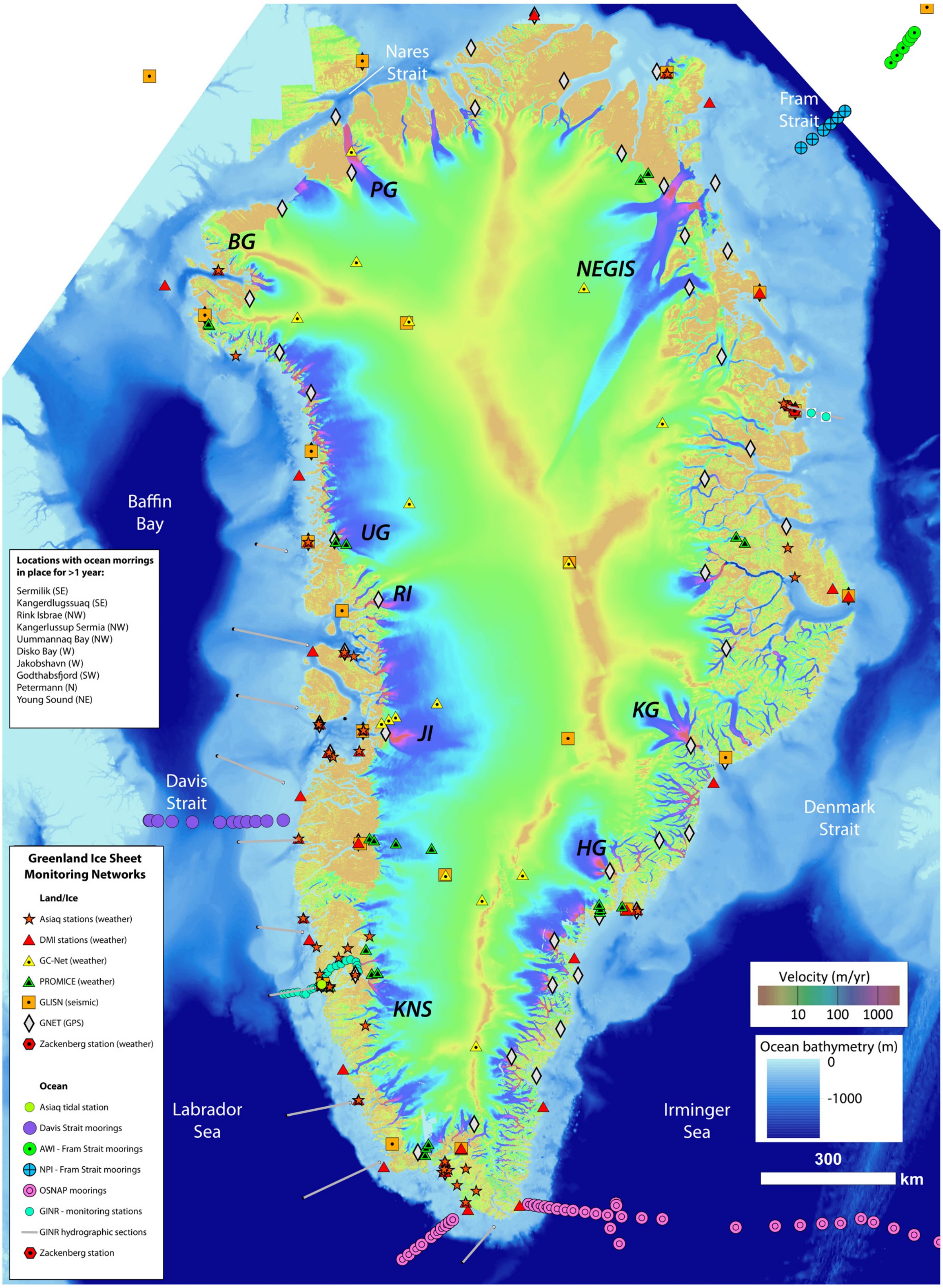

FIGURE 5 | Map of primary existing *in situ* networks and long-term measurements around Greenland, overlaid on a map of ice velocity (Joughin et al., 2011) and bathymetry (Morlighem et al., 2017). Glaciers listed in **Table 2** are identified using labels from **Table 2**.

isotopes ($\delta^{18}O$). The future of the network is uncertain and dependent on funding.

Overturning in the Subpolar North Atlantic Program[2] is an international trans-basin observing system to measure the meridional overturning circulation through mooring arrays (**Figure 5**), repeat hydrographic transects, and glider deployments (Lozier et al., 2017). The observing network, which includes two mooring arrays on the southeast and southwest Greenland shelves and slopes, was installed in 2014 and currently funded through 2020. It is expected that it will be maintained for a decade.

Hydrographic Surveys

The Greenlandic fisheries industry has records, dating back to 1990, of bottom temperature collected during bottom trawler shrimp density surveys off the southwest coast (e.g., Holland et al., 2008). Approximately 50% of the stations are reoccupied annually. The Icelandic mackerel survey on the east coast has hydrographic measurements starting from 2013 that extend from Greenland to Iceland and Norway.

Hydrographic transects in Godthåbsfjord have been conducted since 2007 by the Greenland Institute of Natural Resources (GINR) and include measurement of physical, biological, and chemical variables (**Figure 5**). Ice-free conditions in the fjord mean this survey is conducted year-round from small vessels. One station near Nuuk is monitored monthly, where a suite of ecosystem sampling is conducted in concert with the hydrographic observations. Ecosystem monitoring is being carried out only at a few other sites around Greenland, but resources are limited and marine ecosystem observations only begin in 2002. Moorings have been maintained during the last decade at several locations.

Hydrographic transects in West Greenland: GINR also monitors across the continental shelf of west Greenland during yearly surveys (**Figure 5**) in June and July[3]; previously these surveys were handled by DMI on behalf of the Greenland Institute of Natural Resources (e.g., Myers et al., 2009). Additionally CTD measurements are collected inshore during yearly fishery surveys in Maniitsoq, Disko Bay, Uummannaq, and Upernavik.

The Oceans Melting Greenland project is a 5-year NASA program that began in 2015 to observe water temperatures around the coast of Greenland (**Figure 5**) and measure how marine terminating glaciers react to the presence of Atlantic Water (Fenty et al., 2016). The project consists of annual aerial ice topography measurements and gravimetry of glacier margins and the deployment of 250 Airborne expendable CTD probes (AXCTDs) to measure the properties and extent of Atlantic Water around the coast.

The GEOTRACES project is an ongoing, coordinated international activity to quantify the supply, removal, and distribution of bioessential micronutrients (such as iron) in the ocean. The completed cruise sections GA01 (North Atlantic/Labrador Sea), GN02 (Labrador Sea/Baffin Bay) and GN05 (Fram Strait) provide an invaluable dataset to measure trace chemical species in the ocean around Greenland. The GN05 section was notable for proceeding to sample within close proximity to the 79N glacier and the GA01 section includes shallow shelf stations which show a terrestrial influence on shelf water properties. Whilst the GEOTRACES program has an intentional offshore focus, there is now a clear possibility of process studies to bridge the gap between these extensive offshore sections and fjord/shelf regions to understand how far offshore meltwater and glacially derived particles influence the biogeochemical cycling of essential micro-nutrients in the ocean.

The Labrador Sea Monitoring Program of Fisheries and Oceans Canada has collected physical, chemical, and biological observations along a hydrographic transect across the Labrador Sea (corresponding to Atlantic Repeat Hydrography Line 7 West of the World Ocean Circulation Experiment) since 1990. Measurements span Hamilton Bank on the Labrador Shelf to Cape Desolation on the Greenland Shelf. The transect is occupied annually, although frequency is dependent on funding (Yashayaev and Loder, 2017).

Autonomous Sampling

Large scale ocean properties can be obtained from the Argo float program that, since 2006, maintains a global array of more than 3000 free-drifting profiling floats that measure hydrographic properties in the upper 2000 m of the ocean (Roemmich et al., 2009). This program is complemented by the Biogeochemical-Argo float program (Claustre et al., 2010; Gruber et al., 2010), which alongside physical parameters collects biogeochemical measurements. These floats are not useful on the Greenland continental shelf but do provide boundary conditions to monitor long-term average ocean basin property changes around Greenland.

Water property information is also obtained by tagging marine mammals, and a central repository for these data already exist in the international Marine Mammals Exploring the Ocean Pole to Pole program (Treasure et al., 2017). These temperature/salinity profiles provide useful data on the continental shelves (e.g., Sutherland et al., 2013) or offshore (Laidre et al., 2010; Grist et al., 2014), and are potentially a way forward for collecting more *in situ* data inside fjords (e.g., Mernild et al., 2015) as well as a connection to the ecosystem response of higher-trophic level animals influenced by Greenland's glacial fjords (Laidre et al., 2016).

Remote Sensing

Remote sensing data products can provide important oceanographic information (such as sea surface salinity and temperature), but are not currently generated at the scale that is useful for GrIOOS. A few of these products are potentially useful for fjord-scale processes, such as subglacial outlet plumes, sea-ice cover, iceberg drift and biological productivity (ocean color). However, satellites are limited in their ability to observe subsurface features (e.g., phytoplankton blooms, glacial and sediment plumes) that are relevant to GrIOOS science goals. Sea surface height can be measured via satellite altimetry, but with challenges near the coast and with limited

[2] www.o-snap.org

[3] https://archive.nafo.int/open/sc/2015/scr15-001.pdf

coverage at high latitudes (Cipollini et al., 2016). Sediment plumes can be monitored by MODIS Aqua/Terra and Landsat 8, and ocean color measurements (characterizing biomass of primary producers and productivity) are collected by SeaWiFS, MODIS, and Sentinel 3-A, among others. Most of these variables, however, are considered ancillary to the essential ocean variables for GrIOOS.

Remote sensing of sea ice can include active and passive microwave estimates of the thermodynamic state of fast-ice fringes of sea ice, sea ice drift estimates (including export pathways on the west and east sides of Greenland), presence of significant freshwater sea ice, sea ice dynamic properties through coupling to glacier solid and liquid phase fluxes, and estimates of the optical properties of the sea ice through microwave-optical radiative transfer techniques (e.g., Barber, 2005). Specifically, both Landsat (optical) and Sentinel (optical, radar) satellite imagery can be used to identify sea ice distributions near the Greenland coast. The combination of Landsat and Sentinel imagery allows for the near-daily classification of features after 2016. Prior to the launch of the Sentinel satellites, repeat observations with Landsat occur every 16–18 days since ∼1999. Note that even medium resolution sea ice concentration products, such as 4-km Multisensor Analyzed Sea Ice Extent data (and, in 2015-2016, 1-km resolution data), fail to provide accurate sea ice concentrations in Greenland fjords. Future GrIOOS efforts would include the systematic production of these data at temporal and spatial scales relevant for fjord dynamics.

Glacier and Ice Sheet

Surface Speed

Both optical and radar remotely sensed data can be used to derive velocity data. Optical data has the benefit of multiple bands of data, which can be useful for co-processing velocity with other information, but imaging the ice surface through clouds or darkness is not possible. Radar data avoid these problems but does not include additional bands of data. Satellite coverage for both optical and radar data has expanded substantially over the last two to three decades, with additional satellite launches for both optical and radar instruments planned within the next few years. Velocity data are now available in weekly to monthly time resolution via projects including GoLIVE (Global Land Ice Velocity from Landsat 8 Extraction[4]); ITSLIVE (Intermission Time Series of Land Ice Velocity and Elevation), which will begin in 2019; and NASA MEaSUREs[5], all with key glaciological data hosted at the National Snow and Ice Data Center. Velocity data are also available for more limited areas via the ENVEO Cryoportal[6], CPOM Data Portal[7], and Technische Universitat Dresden[8]. The European Space Agency's (ESA) climate change initiative for the GrIS has operationally produced a number of relevant remote sensing data products including ice sheet velocity, calving front position, surface elevation change and grounding line position. These datasets are updated semi-annually and are freely available (e.g., Mottram et al., 2018).

Terminus Position

As a result of recent interest in the various processes influencing glacier termini there has been renewed interest in tracking glacier terminus changes over time (Bjørk et al., 2012). Currently yearly observations of the terminus position are available (Murray et al., 2015; Joughin et al., 2017) for the entire ice sheet, including via NASA and ESA. Regional subsets of glaciers have more frequent observations of terminus position, up to twice-monthly in some regions (e.g., Seale et al., 2011; Carr et al., 2015; Murray et al., 2015; Catania et al., 2018), but these records are dispersed among individual researchers or archives. GrIOOS will need to build on these existing efforts to establish a consistent and complete terminus position data stream.

Surface Elevation

From 1993 to 2003 surface elevation data have been acquired over the GrIS to understand glacier dynamic evolution in response to climate forcing with NASA's airborne laser altimeter (Krabill et al., 1999; Abdalati et al., 2002). From 2003 to 2009 NASA's ICESat mission provided laser altimetry data over the entire ice sheet and altimetry is now being continued through to the recent launch of ICESat-2. In the interim, NASA's Operation Icebridge has provided continuous elevation data[9]. Combined, these data are used to constrain modeled estimates of elevation change for the entire ice sheet over the entire duration that observations are available (Csatho et al., 2014). In addition to laser altimetry, surface elevation change observations from additional airborne and satellite missions have enabled the creation of digital elevation models (DEMs) for the GrIS. In some cases these DEMs have been created from historical air photos acquired in stereo to produce elevation data extending back to the late 1970s (Korsgaard et al., 2016). Additional DEMs have been created from the commercial vendor DigitalGlobe through its provision of high-resolution optical imagery of the polar regions over the launch of six WorldView spacecraft (Shean et al., 2016). DigitalGlobe coverage began in 2009 with sporadic coverage until 2012, with the periphery of the GrIS covered with stereo-pairs every year since. Data are currently processed and made available through the Polar Geospatial Center (Porter et al., 2018). The Polar Geospatial Center also serves time-stamped ArcticDEM strips. A useful summary of the last 25 years of surface elevation change is given by Sørensen et al. (2018) based on ESA Greenland data from ERS, ENVISAT and Cryosat-2.

Surface Runoff and Subglacial Discharge

The estimate of ice sheet surface mass budget and runoff, routed through individual glacier catchments, is critical for quantifying the spatio-temporal distribution of meltwater-driven terminus melt as well as freshwater discharge and the timing and magnitude of biogeochemical transports. However, ice sheet SMB and runoff continues to be poorly validated at the outlet glacier scale because of the difficulties involved in measuring

[4]nsidc.org/data/golive

[5]nsidc.org/data/measures

[6]cryoportal.enveo.at

[7]www.cpom.ucl.ac.uk/csopr/iv

[8]data1.geo.tu-dresden.de/flow_velocity

[9]icebridge.gsfc.nasa.gov

subglacial discharge. Observations of SMB are made at the locations of automatic weather stations (van As et al., 2011) and from snowpits and shallow firn cores on e.g., repeat transects (Machguth et al., 2016). This data has been key to evaluating SMB and runoff derived from regional climate models (e.g., Langen et al., 2017) that has been used in the past for driving ice sheet and coupled ocean-ice sheet models (e.g., Slater et al., 2015). However, while these observations will continue to be important the on-ice environment at outlet glaciers is typically not conducive or indeed accessible to the kind of on-ice instrumentation required to measure surface accumulation, melt and runoff particularly over long time periods.

Various researchers have discretized time-series surface mass balance data (described below) into regional or individual glacier catchments using surface and bed topography of the ice sheet to quantify how much runoff drains into a particular catchment (e.g., Carroll et al., 2016; Jackson et al., 2017). The timing and delivery location of meltwater runoff to the terminus has been cross-checked with identification of visible sediment plumes on the fjord surface from satellite images and the formation of terminus embayments where enhanced terminus change occurs as a result of significant melt at depth (Fried et al., 2015). However, not all subglacial conduits will deliver sediment-laden water that reaches the fjord surface (Carroll et al., 2016). Empirically most (∼80%) of the runoff transits through a small number of channels that have the largest impact on terminus retreat (Fried et al., 2018). Validation of runoff has occurred in regions with land-terminating ice, for example in the Watson River catchment in southwest Greenland (Smith et al., 2017), with good agreement between proglacial discharge and surface melt estimated via regional climate model (van As et al., 2017).

Atmospheric Measurements

Weather Station Data

Weather observations in Greenland are perhaps some of the longest time-series and most mature climate information available, with DMI and Asiaq (Asiaq Greenland Survey) maintaining a network of meteorological stations around the margins of the GrIS (and at Summit Station), in some cases back to 1784. These data are freely available to download from the DMI homepage and are fully quality controlled (a new open data policy at DMI includes the development of a data portal that will considerably simplify the process of accessing existing data and other data or products, such as forecast model output that is not currently routinely available). As a national weather institute, DMI stations conform to World Meteorological Organization standards in terms of siting and sensors. There are also radiosondes operated at two sites on the coast of Greenland giving atmospheric profiles. PROMICE is a Danish government-funded monitoring network with the goal of providing consistent long-term observations to calculate mass loss by the energy budget method using weather station observations (precipitation, surface temperature, radiation, humidity, wind speed, and direction) from a network of sites around the GrIS (van As et al., 2011, 2017). This network consists of > 23 automated weather stations distributed in the ablation zone around the GrIS since 2007. The network has large spatial coverage and is expected to be maintained long-term for monitoring mass loss of the ice sheet. The main component of PROMICE is the free online database that includes historical mass balance data, documentation of recent change, and outreach efforts. PROMICE is complemented by GC-NET, a network of AWS in the upper accumulation zone of the ice sheet operated by University of Colorado (e.g., Steffen and Box, 2001).

Dynamical and Statistical Reconstructions

Several methods are used to reconstruct the surface atmospheric state above the GrIS, from which surface mass balance may be derived ice sheet-wide. Global atmospheric reanalysis products assimilate satellite and in-situ data into atmospheric weather models to provide best-possible analyses of the state of the atmosphere, including the GrIS. Examples of such products are ECMWF's ERA-Interim (Dee et al., 2011), ERA-20C (Poli et al., 2016), or NASA's MERRA-2 (Gelaro et al., 2017); for a more complete list, see Lindsay et al. (2014). Because of the limited spatial resolving power of global reanalyses (order of 30 km over Greenland), limited area (i.e., regional) atmospheric or climate models have been developed that use lateral boundary conditions from global reanalyses. Limited area climate models provide hindcast simulations of the regional domain at much higher spatial resolution (order of 10 km) that are calibrated or validated using Greenlandic weather observations, and compute ice sheet-wide surface mass balance. Three major such efforts are the Modèle Atmosphérique Régional (MAR; Fettweis et al., 2017)[10], the Regional Atmospheric Climate Model, version 2 (RACMO2; Noël et al., 2018)[11], and the High-Resolution Limited Area Model, version 5 (HIRLAM5; Langen et al., 2015; Mottram et al., 2017a). Finally, to obtain very high-resolution (order of 1 km) estimates of the surface atmospheric state and implied surface mass balance, statistical downscaling methods have been developed (e.g., Noël et al., 2016; Wilton et al., 2017). In these limited area models, the freshwater discharge from the ice sheet (called runoff) is provided as a time-series across the entire region.

A new Arctic regional reanalysis for 1998–2020, at the extremely high resolution of 2.5 km, will also go into production in 2019–2021 with a specific aim of resolving Greenland's complex topography including fjords. Part of the Copernicus regional reanalysis project and run by the Norwegian, Danish, Swedish, Finnish and Icelandic Meteorological Institutes together with Meteofrance, this represents a major step forward in regional atmospheric data for the Arctic and will provide exceptionally high quality data. The reanalysis is built on the HARMONIE numerical weather prediction system (Bengtsson et al., 2017) used operationally in Europe, Greenland and Iceland and verified to be of very high quality over the ice sheet including in the fjords (Mottram et al., 2017b).

Other Integrated Networks

Greenland Ecosystem Monitoring (GEM)

Greenland ecosystem monitoring is an integrated monitoring and long-term research program on ecosystems and climate

[10] www.cryocity.org/mar-explorer.html

[11] www.projects.science.uu.nl/iceclimate/models/racmo.php

change effects and feedbacks in the Arctic. Since 1994, the program has established a coherent and integrated understanding of the ecosystem functioning in a highly variable climate, which is based upon a comprehensive, long-term inter-disciplinary data collection carried out by Greenlandic and Danish monitoring and research institutions, primarily at the three main field stations: Nuuk in low arctic West Greenland, Qeqertarsuaq in Disko Bay, and Zackenberg in high arctic Northeast Greenland[12]. GEM sites also have significant fjord measurements that could be useful in this context.

Greenland Integrated Observing System (GIOS)

Greenland Integrated Observing System is a broad institutional collaboration between research institutions to integrate and collaborate on long-term measuring programs in Greenland. This has so far resulted in the Arctic gateway, Isaaffik homepage[13] where all measuring programs and projects in Greenland are visible. NSF has recently added their project and activities also. A combined GIOS program is under development and discussions on how to make this a part of an Arctic science hub in Greenland is currently taking place.

DMI Winter Observatory and Ongoing NW Greenland Observations

DMI runs an ongoing (started in 2011) winter monitoring program based in Qaanaaq in northwest Greenland. The observational effort relies on the engagement of and cooperation with local hunters and traditional knowledge has been taken into account in the design and timing of components, which include:

1. In December, a sled team instruments a section across the fjord with ice tethered ocean moorings, ice mass balance buoys, and an on-ice automated weather station. Instruments log data until June and are maintained by local hunters.
2. In March, when conditions are favorable for sled journeys, a week long oceanographic CTD campaign is conducted seaward from the glaciers at the head of the fjord.

In addition, DMI operates a manned station in Qaanaaq that offers logistic support for the activities in the fjord, including recent Japanese research activities at Bowdoin Glacier (Sugiyama et al., 2015).

Baffin Bay Observing System

Canada leads a new Canada Excellence Research Chair program that will focus efforts on fresh water-marine coupling in Baffin Bay. The program is designed as phase one to a Baffin Bay Observing System (Rysgaard and BBOS Committee, 2017) that is being developed as a parallel effort to GrIOOS. The Baffin Bay Observing System is a unique 'big science' idea building on a strong collaboration between national and international Universities, Inuit organizations, communities on both sides of Baffin Bay, government ministries and agencies, defense, shipping and marine based companies, various technology providers, industry, coastal and offshore fisheries and colleges, all focused around a single collaborative world-class-bay-wide observatory[14]. It is being initiated in the northern part of Baffin Bay through strong collaboration between the Arctic Science Partnership[15] and the Pikialasorsuaq Commission[16].

The Canadian program will develop knowledge, tools, and models that will improve understanding of how freshwater fluxes (solid and liquid phase) from glaciers, ice caps and the GrIS, are delivered to the adjacent marine system and what impacts this freshwater has on physical, biological, and geochemical processes in the marine system. The geographic focus of the work will be Baffin Bay, with investigations of both Canadian and Greenlandic glaciers exporting freshwater to the Bay. Process studies will also include *in situ* studies of the North East Greenland Ice Stream, Petermann Fjord, Ellesmere and Baffin Island Glaciers, and ice fluxes exiting the west side of the GrIS into Melville Bay. Discussions have begun with how to link the field stations sites of the CERC program to the station sites of GrIOOS and how to engage the CERC research themes in this international collaboration. An Inuit led community based monitoring program will be developed through a unique partnership with the Inuit Circumpolar Council focused on the Pikialasorsuaq, near the North Open Water Polynya area of northern Baffin Bay. The northern end of Baffin Bay is a key area for both renewable and non-renewable resources, and an excellent candidate for an Inuit-managed marine management area.

GNET: Greenland Network of GPS Stations

GNET (Greenland GPS Network) – a network of GPS stations, located on the bedrock, initially deployed and maintained by funding from NSF – is now owned and operated by the Danish Technical University under contract to Ministry of Energy, Climate and Utilities. The stations have proved to be successful in quantifying precise crustal movements related to changes in ice load and, as such, are therefore a valuable source of validation of both local and ice sheet wide mass changes.

ORGANIZATION/FRAMEWORK

It is envisioned that GrIOOS will be achieved through the coordination of long-term measurements at multiple sites collected by different institutions and nations. It can build on existing efforts to build long-term records of certain oceanic, atmospheric and/or glaciological parameters at certain sites which have, so far, been occurring in isolation one from the another. By identifying the measurements needed at each site, and describing the data collection and processing protocols – GrIOOS will provide a framework that enables coordination amongst the different efforts and a structure for making the data available to the broader scientific community.

[12] http://g-e-m.dk
[13] https://www.isaaffik.org
[14] http://www.researchgate.net/project/Baffin-Bay-Observatory-System
[15] http://www.asp-net.org
[16] http://pikialasorsuaq.org/en/

Overall Governance Structure

The international and multidisciplinary nature of GrIOOS calls for a governance structure that serves several overarching purposes: (i) efficient pooling and optimal use of the limited observational assets to fulfill the science goals; (ii) efficient communication, coordination, and collaboration across a heterogeneously structured international and multi-disciplinary science team, funding agency landscape, and organizational/government representation; and (iii) successful and sustained execution of GrIOOS. Similar challenges have been successfully tackled, or are being addressed by international programs, such as the Southern Ocean Observing System[17] the Integrated Atlantic Ocean Observing Systems[18] or the Deep Ocean Observing Strategy[19] (see Levin et al., 2019). To achieve these goals, we propose the establishment of a governance structure as follows:

(i) An Executive Committee oversees the proper execution and efficient functioning of GrIOOS at an operational level. The Executive Committee also directs a Project Management Panel, which is responsible for, and responsive to, day-to-day operational aspects.
(ii) A Scientific Steering Committee ensures that GrIOOS is working toward achieving the science goals.
(iii) Working with the Executive and Scientific Steering Committees are several panels and boards:

- An External Advisory Board – to oversee GrIOOS, make recommendations where needed;
- A Data Management Panel – its role is to implement and oversee an ambitious data management plan that follows FAIR principles (see Data Protocol and Management).
- A Community Engagement and Outreach Panel – its role is to engage scientific, end user, stakeholder, and local communities in various aspects of the program (see End Users);
- A Liaison team of international/interagency members, working on matters concerning international and/or interagency (see International/Interagency Liaisons).

Data Protocol and Management

A vision for GrIOOS is to implement the principle of FAIR data (Wilkinson et al., 2016) within the complexities of a multi-disciplinary international program. In the following we list some of these tasks and provide further comments, where applicable.

Pre-deployment phase: Much can be gained in terms of efficient data management by developing a comprehensive sensor information system, which consists of creating and managing metadata of devices, sensors, and variables ahead of their deployment. Likewise, data quality control policies and best practice procedures should be established. Finally, data sharing policies and procedures in line with the FAIR principles should be formulated and agreed upon early on in the project.

Post-deployment phase: An infrastructure is required for data acquisition and transmission to an archiving facility that can further process the data. As with most observing networks, the value of a network is augmented by serving multiple communities and stakeholders (but without compromising its primary purpose). Real time data dissemination should be considered where feasible for variables and/or measurement platforms; primary applications of real time dissemination are ingestion of these observations in forecast models, as well as operational and local community support. An initial goal of the GrIOOS executive committee will be to identify mature variables (and corresponding platforms) for real time dissemination. Collaboration with the operational branch of the Joint Technical Commission for Oceanography and Marine Meteorology of the World Meteorological Organization and UNESCO's Intergovernmental Oceanographic Commission will be explored to enable real time data transmission.

After transmission, metadata tagging should be completed (where needed) and the data set curated. It should be ensured that the data are searchable and accessible using standard metadata formats that are supported by common protocols, web services, and search engines (Google, DataCite, WorldCat, EOSDIS).

In considering data storage, archiving, and server infrastructure, GrIOOS should establish the roles of existing data portals that are recognized by the World Data System (major portals in the U.S. are http://arcticdata.io and http://nsidc.org; in Europe: http://pangaea.de and http://ices.dk). Interoperability between them should be assessed or invigorated. Finally, GrIOOS should address how to ensure the longevity and sustainability of the data infrastructure beyond the conventional life cycle (from measurement/creation to post-analysis archiving[20]) of the data sets.

Several frameworks exist to date that have implemented (or work toward implementing) some of the tasks listed above. The U.S. National Science Foundation's Arctic Observing Network program requires data to be immediately available. PROMICE demonstrates that near-real time data are important, valued, and successful. Quick access to data is key either centralized or via a standardized metadata structure that enables data access in the cloud.

A well-developed data infrastructure that succeeds at data integration (i.e., crossing of ice-ocean-atmosphere divide as well as the synthesis of remote-sensing and *in situ* observations) has the potential of creating transformative science through simultaneous accessibility of diverse and heterogeneous, spatio-temporally tagged geophysical parameters. In such a way, the disciplinary "sparse data" problem may turn into a multi-disciplinary "big data" opportunity that lends itself to emerging tools of big data analytics or coupled Earth system data assimilation. Another important aspect of the data infrastructure to be developed is the evaluation process to measure the success and impact of the observing system itself. Such metrics would include data portal access and usage, as well as recording who is using the observations (e.g., academia, industry, other stakeholders).

[17]http://www.soos.aq
[18]http://atlanticblueprint.net
[19]http://www.deepoceanobserving.org
[20]https://www.dataone.org/data-life-cycle

End Users

The data provided by GrIOOS targets a diverse array of end-users from the governmental, non-profit, academic, industrial, and local communities. These observations are needed to improve ice, ocean, atmospheric and earth system models in which the processes governing glacier/ocean exchanges are currently absent or represented through parameterizations that have not been validated by field measurements. GrIOOS data can support improved parameter development. Additional identified users include local Greenlandic and Canadian communities searching for information on real-time ocean temperatures, sea ice coverage, nutrient levels, or productivity in their nearby fjords, and national governments searching for information on iceberg hazards, long-term trends in water properties, or glacier melt predictions that might drive local hydroelectricity. Other end-users are the international iceberg hazard community, which includes the International Ice Patrol (Murphy and Cass, 2012) and Canadian efforts (Crawford et al., 2018), as well as the marine mammal community (Roquet et al., 2017; Treasure et al., 2017). In addition to governmental entities, GrIOOS data will serve local and international fisheries, and local tourism industries that rely on both the ice and ocean environment.

To make GrIOOS data available to these communities, and gather feedback on future developments, GrIOOS will hold inclusive annual meetings. Beyond these meetings, GrIOOS will maintain an active program website and data platform that will be a natural intellectual gathering location for these groups to exchange data and ideas. As needed GrIOOS will hold open workshops on data and uses, as well as update the program website with community tools, tutorials, and wikis; definition of metrics of progress; regular communication of progress; and requests for input at public forums. These activities will be overseen by the Community Engagement and Outreach Panel.

On the outreach side, one prime example is the world heritage site Ilulissat Icefjord where significant increase in tourism is expected to view the impressive icebergs and fjord system and where a new museum with a significant scientific content is currently under construction. GrIOOS and its community can leverage the high visibility of Greenland in outreach and public education efforts across the globe. The experience of using striking visualizations of scientific data to generate awareness has been successfully demonstrated on the polar portal website[21] where a broad array of mostly near real-time data from models and observations in Greenland as well as the wider Arctic receives around 180,000 page impressions per year. The outreach potential of the polar portal is demonstrated by a teacher-led initiative currently underway and funded by the Danish government to develop teaching resources based on polar portal datasets for Danish and Greenlandic high school students. These resources will be made publically accessible via the site and will be translated into English.

Within the outlined governance structure (see Overall Governance Structure), community connections will ensure that all interested groups are involved in project development and that outputs are widely used. These groups include the modeling community (e.g., the modeling intercomparison project groups), researchers working on surface processes at the ice sheet edge (e.g., the Community Surface Dynamics Modeling Systems community), groups conducting process studies on ice-ocean interactions and fjord environments, biologists and ecologists focused on Arctic flora and fauna, sedimentologists, nutrient flux and biogeochemistry experts, industry members, local communities and hunters, and regional governments.

[21] polarportal.dk

International/Interagency Liaisons

Major roles of the Liaison team are to maintain efficient communications between agencies and foundations at the national and international level.

- In Europe, the team will establish primary liaisons with institutions and organizations in Greenland (including its government) and Denmark, in particular Asiaq, GINR, GEUS, DMI, Danish Technical University, Aarhus University, Københavns University, PROMICE, and GEM; see also section "Other Integrated Networks." Strong links will also be established with institutions, organizations, and governments of other countries that conduct significant research in Greenland, such as Norway, United Kingdom, Germany, Sweden, and Switzerland.
- In the U.S., lines of communications will be established with both inter-agency organizations, such as the Interagency Arctic Research Policy Committee (IARPC), Interagency Ocean Observation Committee (IOOC), US CLIVAR, Arctic Research Commission of the United States (USARC), Arctic Research Consortium of the United States (ARCUS), as well as directly with major funding agencies (e.g., NASA, NSF, USGS).
- In Canada, one primary liaison will be through the University of Manitoba. Government involvement will be sought through Fisheries and Oceans Canada and Environment and Climate Change Canada, with particular reference to shared jurisdiction of Baffin Bay. Another important link is with the Inuit Circumpolar Council, with particular connections to similar councils in Greenland and Canada through the Pikiialasorsuaq Partnership in Baffin Bay.
- Internationally, we will strengthen or establish links to international organizations or programs that are engaged in GrIOOS related themes, e.g., CliC, International CLIVAR, GEOTRACES, Arctic Council. In addition, we will seek to include efforts by groups in all other countries that are engaged in GrIOOS related efforts.

MOVING FORWARD

The case for an integrated GrIOOS is clear: Greenland's fjords and outlet glacier regions are key connections between the open ocean and the interior ice sheet that are not currently monitored systematically. We plan to establish a GrIOOS network to collect long-term data on essential variables from key ice sheet-ocean locations that cover a range of glacier/fjord configurations, different oceanic basins, and climatic regimes. Essential measurements to be collected at these sites include oceanic (temperature, salinity, pressure, sea ice cover, iceberg production and distribution, and basic biogeochemical parameters in the fjord and nearby shelf), glaciological (ice velocity, surface elevation and ice thickness, terminus position, and subglacial runoff) and atmospheric (wind, temperature, precipitation, and radiation). Bathymetry and bedrock are foundational data sets needed for any GrIOOS site. Together, these data provide the information needed to understand and project ice sheet-ocean behavior and change and its impact on the ocean.

Over the next few years, the continued development and maintenance of GrIOOS will require close international collaboration. GrIOOS' implementation will need to be coordinated amongst different countries, paying close attention to minimizing costs and optimizing shared logistics. Several glacier/fjord locations that have ongoing observational programs may be designated GrIOOS sites, and a protocol for the establishment and endorsement of future sites will be formalized through our governance structure. Data processing protocols and data sharing practices will also be formalized. Quick, open, and centralized access to data is critical to all GrIOOS users.

GrIOOS will represent a step-change in our observational capacity around the GrIS and will drastically improve our understanding of mechanisms that influence sea level rise, increased freshwater flux to the North Atlantic Ocean, and local and regional ecosystem effects from a changing ice sheet. A successful GrIOOS will satisfy the needs of many distinct end-users, from the scientific community of global climate modelers and ice-ocean researchers to local and regional government entities around Greenland.

DATA AVAILABILITY

No datasets were generated or analyzed for this study.

AUTHOR CONTRIBUTIONS

FS, DS, LS, GC, PH, and TM conceived and wrote the paper with contributions from MC, KL, DB, SR, RM, SO, MH, and LM.

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A Harmonized Nitrous Oxide (N_2O) Ocean Observation Network for the 21st Century

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Nitrous oxide (N_2O) is an important atmospheric trace gas involved in tropospheric warming and stratospheric ozone depletion. Estimates of the global ocean contribution to N_2O emissions average 21% (range: 10 to 53%). Ongoing environmental changes such as warming, deoxygenation and acidification are affecting oceanic N_2O cycling and emissions to the atmosphere. International activities over the last decades aimed at improving estimates of global N_2O emissions, including (i) the MarinE MethanE and NiTrous Oxide database (MEMENTO) for archiving of quality-controlled data, and (ii) a recent large-scale inter-laboratory comparison by Working Group 143 of the Scientific Committee on Ocean Research (SCOR). To reduce uncertainties in oceanic N_2O emission estimates and to characterize the spatial and temporal variability in N_2O distributions in a changing ocean, we propose the establishment of a harmonized N_2O Observation Network (N2O-ON) combining discrete and continuous data from various platforms. The network will integrate observations obtained by calibrated techniques, using time series measurements at fixed stations and repeated hydrographic sections on voluntary observing ships and research vessels. In addition to exploiting existing oceanographic infrastructure, we propose the establishment of central calibration facilities in selected international laboratories to improve accuracy, and ensure standardization and comparability of N_2O measurements. Final data products will include a harmonized global N_2O concentration and emission fields for use in model validation and projections of future oceanic N_2O emissions, to inform the global research community and policy makers.

Keywords: nitrous oxide, observation network, oceanic distribution, oceanic emissions, calibration

INTRODUCTION

Nitrous oxide (N_2O; laughing gas) is an atmospheric trace gas, which accounts for 6% of tropospheric warming by greenhouse gasses, and is a major ozone-depleting compound in the stratosphere (Ravishankara et al., 2009; IPCC, 2013; WMO, 2014). Emission estimates indicate that the oceans may contribute 10 to 53% of combined natural and anthropogenic N_2O sources (Anderson et al., 2010; Ciais et al., 2013). N_2O has been measured in the water column of all major ocean basins, in most marginal seas and in numerous estuaries (Kock and Bange, 2015; Murray et al., 2015), with measurements from the surface mixed layer down to 9800 m in the deep Izu-Ogasawara Trench (Kawagucci et al., 2018). These and other studies show that N_2O concentrations may vary over three orders of magnitude from the open ocean to coastal shelves and semi-enclosed basins. Concentrations range from <1 nmol L^{-1} in the permanently anoxic deep basin waters of the Black Sea and Cariaco Trench (Hashimoto et al., 1983; Westley et al., 2006) to ≈1000 nmol L^{-1} in coastal near-surface waters off Peru (Arévalo-Martínez et al., 2015) and ≈1500 nmol L^{-1} in the suboxic deep waters of the Baltic Sea (Rönner, 1983). Some estuaries may reach similarly high concentrations (Barnes and Upstill-Goddard, 2011).

While the oceans are clearly a major natural contributor to atmospheric N_2O, quantitative estimates remain highly uncertain (Buitenhuis et al., 2018). This uncertainty reflects the low number of marine N_2O measurements to date, as compared to, for example, CO_2 [see e.g., (Bakker et al., 2016)], and the lack of information on (i) seasonal and inter-annual variability, (ii) land-ocean gradients, (iii) the effects of small scale/mesoscale features (Grundle et al., 2017) and (iv) extreme events such as storms (Naik et al., 2008). There is also uncertainty in the relative importance of the various biological processes driving the production and consumption of N_2O in oceanic waters, and their potential responses to changing oceanic conditions (Bange et al., 2010). Likewise, the influence of sea ice on N_2O emissions from high-latitude ecosystems is currently unknown (Vancoppenolle et al., 2013). Randall et al. (2012), for instance, showed that sea ice formation and melting cycles can reverse the direction of the N_2O fluxes across the ocean/atmosphere interface. Yet, the overall impact of these processes on the annual cycle is still unclear.

Oceanic N_2O production and consumption principally occurs in subsurface and deep waters. Microbial nitrification (N_2O is a by-product of ammonia oxidation to nitrite), partial denitrification (reduction of nitrate to N_2O), and nitrifier-denitrification (i.e., nitrifier switching to nitrite reduction under low O_2 conditions) are considered to be the main oceanic N_2O production pathways, whereas, the main N_2O sink is via reduction to N_2 by denitrification in anoxic waters (Bange et al., 2010). Extreme accumulation of N_2O resulting from nitrification and/or denitrification has been found at oxic/anoxic boundaries within oxygen minimum zones (OMZ) of the eastern tropical North/South Pacific Ocean and the Arabian Sea, and also in coastal shelf waters (Bange et al., 2010). In addition, several studies indicate N_2O production via nitrification in surface waters of the open ocean (Dore and Karl, 1996; Law and Ling, 2001; Morell et al., 2001) and in estuaries (Barnes and Upstill-Goddard, 2011), as well as its possible consumption during microbial N_2O fixation (Farías et al., 2013; Cornejo et al., 2015).

Environmental changes such as ocean warming (and associated changes in stratification and ice coverage), acidification, deoxygenation, and eutrophication due to increasing anthropogenic inputs of nutrients (via rivers and atmospheric deposition), may significantly alter N_2O production and consumption, its distribution patterns and, ultimately, its release to the atmosphere (Kroeze et al., 2005; Zhang et al., 2010; Suntharalingam et al., 2012; Rees et al., 2016; Myllykangas et al., 2017). Indeed, model projections that account for ocean warming and atmospheric nitrogen deposition show a net decrease of 4 to 24% in future global oceanic N_2O emissions during the 21st century (Martinez-Rey et al., 2015; Landolfi et al., 2017; Battaglia and Joos, 2018). One model projection suggests that the decrease of N_2O emissions in the 21st century might be followed by a substantial increase of the N_2O emissions in the 22nd century (Battaglia and Joos, 2018). The large degree of uncertainty in future N_2O emission projections results partly from the limitations of existing N_2O concentration data used in model parameterizations and validation. These current data sets are not yet cross-calibrated (their comparability is limited due to missing standard measurement protocols), and are biased by poor spatio-temporal coverage of the ocean (Kock and Bange, 2015).

The importance of additional, routine oceanic N_2O measurements is recognized by the Global Ocean Observing System (GOOS) program, which recently added N_2O to its list of Essential Ocean Variables (EOV)[1].

To reduce uncertainties in current global N_2O marine emission estimates, better constrain and understand temporal and spatial variability, and improve future projections of N_2O concentrations in a changing ocean, we propose the establishment of a harmonized Global N_2O Ocean Observation Network (N2O-ON).

OBSERVATION NETWORK COMPONENTS

Measurement Techniques

The analysis of N_2O at the sea surface and in the ocean interior differs in both measurement approach and the required analytical precision. While water column N_2O concentrations are usually determined using discrete seawater samples, state-of-the-art surface water measurements increasingly use air-water equilibration systems coupled to optical sensors in a continuous mode. In this section we briefly review the development of marine N_2O observations, discuss a coordinated approach to method calibration, and identify emerging technologies that should contribute to improved data quality and spatio-temporal coverage within N2O-ON.

[1] www.goosocean.org

Discrete Measurements

The first study of oceanic N_2O distributions took place nearly 60 years ago in the South Pacific Ocean (Craig and Gordon, 1963), and was followed by measurements in the North Atlantic Ocean during the late 1960s/early 1970s (Junge and Hahn, 1971). A later study in the Sargasso and Caribbean Seas introduced the concept of "$\Delta(N_2O)$" [= $c_{measured}(N_2O) - c_{equilibrium}(N_2O)$], to quantify the difference between the observed and air equilibrium concentration of dissolved N_2O, and thus examine net N_2O production/consumption (Yoshinari, 1976). The development of a rigorously calibrated electron capture detector (ECD) coupled with gas chromatography (GC) facilitated precise and reliable N_2O measurements (Rasmussen et al., 1976; Cohen, 1977; Elkins, 1980; Weiss et al., 1981). Since those pioneering studies, the increasing availability and comparatively low cost of such instrumentation facilitated a significant increase in data availability.

An important next step was the fundamental work on N_2O solubility in seawater (Weiss and Price, 1980), which promoted the development of equilibration techniques for high-resolution surveys of the surface ocean (Weiss et al., 1992) (see section "Continuous Surface Measurements") and water column N_2O (Butler et al., 1989; Butler and Elkins, 1991). Today, GC-ECD analysis, coupled to headspace equilibration or purge-and-trap techniques, is used by the majority of laboratories worldwide for quantifying dissolved N_2O in discrete seawater samples (Wilson et al., 2018). Even so, mass spectrometric analysis of N_2O is becoming increasingly wide-spread (Capelle et al., 2015; Babbin et al., 2017; Bourbonnais et al., 2017) and may become increasingly important in the future.

An inter-laboratory comparison of oceanic N_2O measurements was recently conducted by the Scientific Committee on Oceanic Research (SCOR) international Working Group (WG) 143[2]. Discrete water samples from the subtropical Pacific Ocean and the Baltic Sea were distributed to participating laboratories (Wilson et al., 2018) for a comparison of accuracy and precision. The samples represented a range of N_2O concentrations, from low concentrations in the oligotrophic open ocean to high concentrations in highly productive and suboxic coastal waters. Recommendations arising from the inter-comparison include (Wilson et al., 2018):

(i) calibration of working gas standards against primary standards,
(ii) incorporation of internal controls (i.e., air-equilibrated seawater) alongside routine sample analysis, and
(iii) the production of high and low N_2O concentration reference seawater for calibrating N_2O measurements across the full range of seawater N_2O concentrations.

Primary gas standard mixtures obtained from atmospheric monitoring agencies will ensure consistency between ocean observations and global atmospheric monitoring networks such as NOAA's Earth System Research Laboratory/Global Monitoring Division (ESRL/GMD[3]), NASA's Advanced Global Atmospheric Gasses Experiment (AGAGE[4]) and the European Integrated Carbon Observing System (ICOS[5]). With accompanying guidelines for discrete measurements in preparation, these recommendations should lead to significant advances in precision and accuracy, thereby improving the inter-comparability of dissolved N_2O measurements and facilitating the detection of seasonal and inter-annual N_2O variability in the near future. Detecting inter-annual N_2O signals is a major goal of N2O-ON, and will require a precision of better than 0.02 nmol L^{-1} (<0.2%). This value is derived from the expected change in N_2O solubility due to an annual surface ocean warming of 0.01°C, and an annual increase of 1 nmol mol^{-1} (ppb) in the atmospheric N_2O dry mole fraction, setting the salinity to 35 assuming no changes in oceanic N_2O sources and sinks.

Continuous Surface Measurements

In addition to the discrete analysis of N_2O, measurements are also conducted by continuous sampling from the shipboard underway seawater supply. Such measurements are made at a fixed depth (generally between 2 and 10 m below the sea surface) and are often accompanied by atmospheric measurements. These underway measurements have benefited from recent technological advances in cavity-enhanced absorption spectroscopy (CEAS), which facilitate rapid and precise N_2O detection at very low atmospheric mole fractions (i.e., in the sub-ppb range). CEAS analyzers coupled to continuous seawater/gas equilibrators (Arévalo-Martínez et al., 2013; Grefe and Kaiser, 2014; Erler et al., 2015; Zhan et al., 2018) are now frequently used to determine N_2O temporal and spatial variability in surface layers of open and coastal oceans, see e.g., (Arévalo-Martínez et al., 2015; Brase et al., 2017; Grefe et al., 2018; Wells et al., 2018). In addition to CEAS, Fourier Transform Infrared (FTIR) analysis coupled to continuous seawater/gas equilibration (Müller D. et al., 2016) has been developed. A ship-board comparison of five analytical systems (incl. four CEAS systems and one FTIR system) for continuous dissolved N_2O measurements was conducted in the Baltic Sea as part of the activities of SCOR WG 143, demonstrating good agreement between measurements obtained from the different systems. Only recently, a Pumped Profiling System (PPS), connected with a liquid degassing membrane coupled with CEAS has allowed real-time, high-resolution, vertically resolved measurements of sub-surface N_2O (Troncoso et al., 2018). N2O-ON will encourage the wider use of these and emerging new technologies where they can contribute to improvements to data quality, measurement frequency and spatial resolution.

Measurements in the Marine Boundary Layer

Accurate estimates of N_2O flux densities across the ocean/atmosphere interface require measurements of the N_2O mole fraction in the atmospheric boundary layer above the ocean, as well as ocean surface N_2O concentrations.

[2]https://scor-int.org/group/143/
[3]www.esrl.noaa.gov/gmd
[4]https://agage.mit.edu
[5]https://www.icos-ri.eu

Atmospheric dry mole fraction can be converted into seawater saturation concentration as a function of seawater temperature, salinity and ambient pressure using an established solubility equation (Weiss and Price, 1980). Atmospheric N_2O dry mole fractions are often measured in parallel with continuous underway measurements on research vessels and on vessels of opportunity (VOS: also often referred to as "Voluntary Observing Ship" routes) (Arévalo-Martínez et al., 2013). As for seawater measurements, N2O-ON advocates the routine rigorous calibration and quality control of accompanying atmospheric data.

The relatively inert nature of the N_2O molecule results in a long tropospheric residence time, leading to well-mixed and regionally invariant global mole fractions (Prather et al., 2015). Consequently, where high quality ship-based atmospheric measurements are unavailable, N2O-ON will encourage use of high quality data from land-based global atmospheric monitoring networks; for example tropospheric N_2O dry mole fractions from ESRL/GMD (see text footnote 3) or AGAGE (see text footnote 4). This will enable the extrapolation of individual campaign results to regional or global scales. Satellite-based N_2O measurements show promise to augment atmospheric data collection at land-based monitoring stations, but these remote sensing observations currently have intrinsically large measurement errors, making them unsuitable for quantifying air-sea N_2O exchange (Xiong et al., 2014; Bernath et al., 2017). With further improvements, however, such approaches have the potential to inform N2O-ON in the future.

Future Enhancements

New CEAS-based instruments allow high quality N_2O isotopolog measurements (Harris et al., 2013). N2O-ON will identify an observational framework that will facilitate deployment of these instruments on selected sustained observation lines to provide additional constraints on the global atmospheric N_2O budget (Rahn and Wahlen, 2000; Bernard et al., 2006; Park et al., 2012), and to potentially provide greater insight into the mechanisms of oceanic N_2O production and consumption (Sutka et al., 2006; Yamagishi et al., 2007).

Although the development of CEAS can considerably improve N_2O monitoring capabilities (see above), the estimation of sea/air N_2O flux densities remains challenging because of the intrinsic temporal and spatial variability in surface ocean N_2O concentrations, and the variability of existing gas exchange parameterizations (Garbe et al., 2014), which reflect the complexity in environmental controls of air-sea gas exchange. Unraveling this complexity, and thereby refining gas exchange parameterizations, is the focus of considerable ongoing research beyond the scope of N2O-ON. However, techniques such as the eddy covariance (EC) method that directly evaluate air-sea fluxes circumvent the need for such parameterizations (Businger, 1986). Going forward, the use of direct flux techniques such as EC in combination with N_2O analysis by CEAS will be encouraged by N2O-ON as a means of enhancing our understanding of N_2O fluxes across the sea surface on a range of temporal and spatial scales.

Observation Platforms

N2O-ON will exploit established and new observation platforms to improve the characterization of spatial and temporal variability in oceanic N_2O concentrations.

Research Vessels

To date, the majority of surface and water column N_2O data have been obtained on board research vessels from discrete samples collected in Niskin bottles on a CTD Rosette (see section "Discrete Measurements"), or from underway surface measurements via a continuous seawater supply (see section "Continuous Surface Measurements"). While the significant contribution of research vessels is beyond question and will be supported by N2O-ON, such vessels have a limited spatial and temporal footprint, with most sampling campaigns not repeated regularly and mainly occurring during the summer. N2O-ON will address this limitation by promoting the use of additional measurement platforms and sustained observational campaigns.

Repeat Hydrographic Lines and Time-Series Stations

Repeat hydrographic sampling programs are important in evaluating variability at the ocean-basin scale and for establishing variability on timescales from seasonal to decadal. For example, N_2O has been measured biannually since 2012 in repeat hydrographic/geochemistry surveys on GO-SHIP[6] section A25 between Portugal and Greenland (de la Paz et al., 2017). The Atlantic Meridional Transect[7] is an example of an annually repeated cruise on which N_2O measurements have been made over two decades (Forster et al., 2009; Rhee et al., 2009; Grefe and Kaiser, 2014). N_2O has been repeatedly measured during the annual Chinese Arctic and Antarctic Expeditions (CHINARE) to the Arctic and Southern Oceans, see e.g., (Zhan and Chen, 2009; Zhan et al., 2015, 2017). Beside these examples, there are few published time-series measurements of open ocean water column N_2O distributions from repeat hydrographic sections (Nevison et al., 1995; Fenwick and Tortell, 2018). Extending and optimizing the distribution and sampling frequency of repeat hydrographic lines is an important future aspiration for N2O-ON, both for open-ocean and coastal regimes.

Temporal variability is also investigated through regular data collection at a small number of fixed time-series stations, which are usually located close to land. Examples include stations off Goa (India), in Saanich Inlet (Vancouver Island, British Columbia), off central Chile, off Hawai'i in the North Pacific subtropical gyre, in the Eckernförde Bay (southwestern Baltic Sea) and in the Strait of Gibraltar (Naqvi et al., 2010; de la Paz et al., 2015; Farías et al., 2015; Capelle and Tortell, 2016; Wilson et al., 2017; Capelle et al., 2018). Considering the important role of coastal regions in the global N_2O cycle (Bange, 2006; Anderson et al., 2010; Ciais et al., 2013), extending the spatial coverage of fixed time-series stations within a coordinated network is a major aspiration of N2O-ON.

[6]www.go-ship.org/

[7]www.amt-uk.org/

VOS Lines

Autonomous measurement systems on established, regular international VOS routes are restricted to near-surface measurements, and thus do not provide depth-resolved N_2O data. Nevertheless, they do have the potential to deliver a comprehensive picture of the temporal and (limited) spatial variability in surface water N_2O distributions. A pilot VOS line N_2O study in the North Atlantic Ocean between Liverpool, United Kingdom, and Halifax, Canada, was conducted in January 2017 by GEOMAR for the EU InGOS program[8]. The EU BONUS INTEGRAL program[9] will establish N_2O surface measurements on two VOS lines in the Baltic Sea between Lübeck/Travemünde (Germany) and Helsinki (Finland) as well as to Kemi (Finland) at the northern tip of the Baltic Sea. The successful long-term operation of CEAS-based measurements of dissolved non-CO_2 greenhouse gasses has already been demonstrated for methane in the Baltic Sea (Gülzow et al., 2011, 2013). Nevertheless, autonomously monitoring of N_2O on VOS lines requires a clean and maintained seawater supply, the oversight of analytical and emergency systems, and rapid instrument turnaround and cleaning during port calls. Although this is logistically challenging, particularly in remote ocean regions, the increased spatio-temporal coverage offered by measurement of near-surface N_2O on VOS routes should be encouraged as a component of N2O-ON.

Other Sampling Platforms

To date, there are no autonomous underwater sensors available for long-term in-situ N_2O monitoring in either the open or coastal ocean. Addressing this gap will require small, robust (resistant to high-pressure, hydrogen sulfide and biofouling) rapid response sensors with low power requirements for long-term deployment. Once developed, these sensors have the capability to decipher oceanic N_2O distributions with unprecedented spatio-temporal resolution. Potential sensor platforms include Bio-Argo floats[10], gliders, coastal/deep sea moorings and mooring arrays, cabled observatories, drifting buoys and lander systems. We advocate a strong focus on the future development of such sensors and their subsequent integration into N2O-ON.

Data Management

MEMENTO

MEMENTO (The MarinE MethanE and NiTrous Oxide database[11]), launched in 2009 (Bange et al., 2009), archives quality-controlled N_2O data from the open and coastal oceans (including estuaries, fjords etc.) (Kock and Bange, 2015). MEMENTO also publishes N_2O data sets, making them publicly and freely available. Regular updates include new datasets, additional meta-information, and the implementation of improved data quality control. As MEMENTO expands, it will adopt best practices for quality control according to the recommendations resulting from inter-comparison exercises (Wilson et al., 2018) and in accordance to existing databases such as the Surface Ocean CO_2 Atlas (SOCAT[12]) and the Global Ocean Data Analysis Project for Carbon (GLODAP[13]). N2O-ON and MEMENTO are clearly complementary and the routine archiving of quality-controlled data in MEMENTO is an intrinsic requirement of N2O-ON.

Ancillary Data

To evaluate the N_2O data derived from N2O-ON, additional standard hydrographic data (i.e., water temperature, salinity, depth) are important. In addition, chemical (i.e., dissolved O_2 and nutrient concentrations, and pH) and meteorological (i.e., air temperature, pressure, wind speed) data should ideally be collected. Most, if not all, of these variables are measured on a routine basis during research cruises, at some time-series stations and on some repeat hydrographic lines (see section "Observation Platforms"). VOS lines could be equipped with continuously operating systems such as the FerryBox[14]. N2O-ON will formally identify a suite of mandatory ancillary measurements and recommend appropriate measurement and/or sample collection alongside N_2O where possible.

BASELINE MEASUREMENTS

Resource constraints (both financial and personnel) preclude the extensive monitoring of N_2O concentrations across the entire global ocean. For this reason, a primary goal of N2O-ON is to develop a highly strategic sampling approach. In **Figure 1**, N_2O seasonal distributions derived from MEMENTO clearly show severe under-sampling of many ocean regions during various seasons, and it is precisely these regions that should be the target of near-term sampling efforts within N2O-ON. The following regions were specifically identified:

- the North Atlantic during December – February,
- the South Atlantic Ocean during March – August,
- the North Pacific Ocean during September – February,
- the South Pacific Ocean during all seasons,
- the North and South Indian Ocean during all seasons,
- the Southern and Arctic Oceans during all seasons, and
- selected marginal seas and major estuaries.

N2O-ON will coordinate N_2O baseline measurements on VOS, establishing these along major international shipping routes crossing the gyres of the major basins of the Atlantic, Pacific and Indian Oceans (**Figure 2**). We propose the establishment of repeat hydrographic lines using research vessels and/or VOS lines to measure N_2O in the surface waters and water column of the Eastern Boundary Upwelling Systems (EBUS) and the Arabian Sea. This could exploit VOS lines transiting

[8]www.ingos-infrastructure.eu
[9]www.io-warnemuende.de/integral-home.html
[10]http://biogeochemical-argo.org/
[11]https://memento.geomar.de
[12]www.socat.info
[13]www.glodap.info
[14]www.ferrybox.com

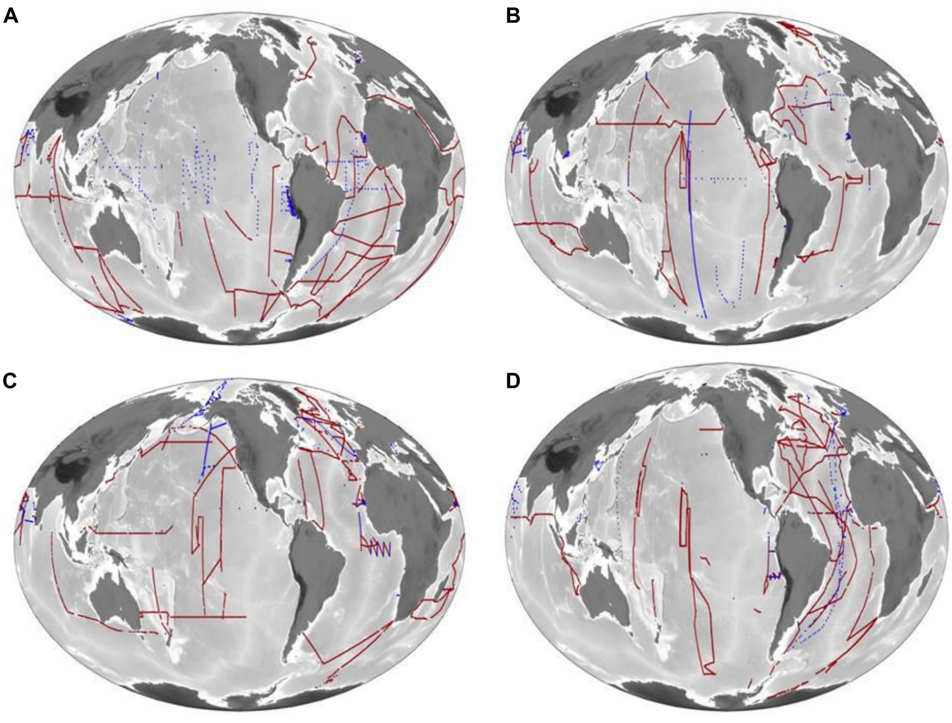

FIGURE 1 | Maps of the distribution of N_2O measurements in **(A)** December, January, February; **(B)** March, April, May; **(C)** June, July, August and **(D)** September, October, November. Red lines indicate continuous surface measurements. Blue dots indicate locations of N_2O depth profiles. Data are from MEMENTO as of October 04, 2018 (https://memento.geomar.de/de).

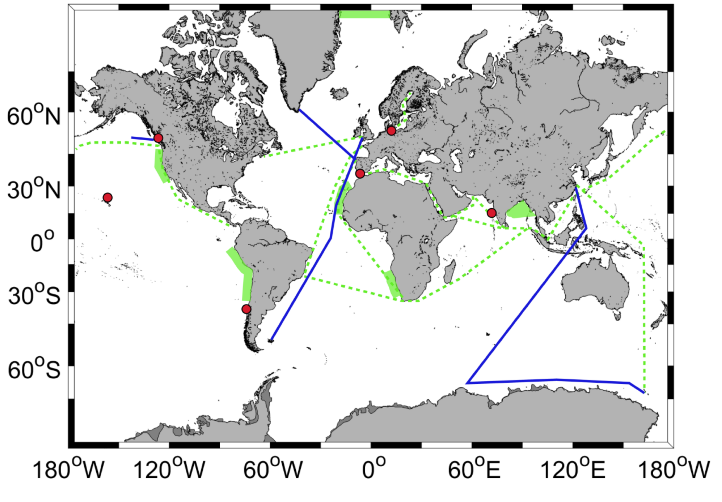

FIGURE 2 | N_2O baseline measurements proposed for N2O-ON. Blue lines/red points indicate currently active repeated oceanographic sections/fixed time-series stations (see text). Dashed green lines indicate prospective VOS lines to be equipped with systems for continuous measurements. Green shaded areas mark key regions for the establishment of new time-series stations.

international shipping routes along the west coasts of North and South America, northwest and southwest Africa, and in the Arabian Sea. Moreover, routine N_2O measurements should be incorporated into the FRAM Ocean Observing System (Soltwedel et al., 2013) in order to close some of the large data gaps in the Arctic Ocean (**Figure 2**).

Incorporating N_2O into the suite of measurements of some established repeat hydrographic sections, such as GO-SHIP[15] or GEOTRACES[16], could provide a basin-scale approach to resolve

[15] www.goship.org

[16] www.geotraces.org/

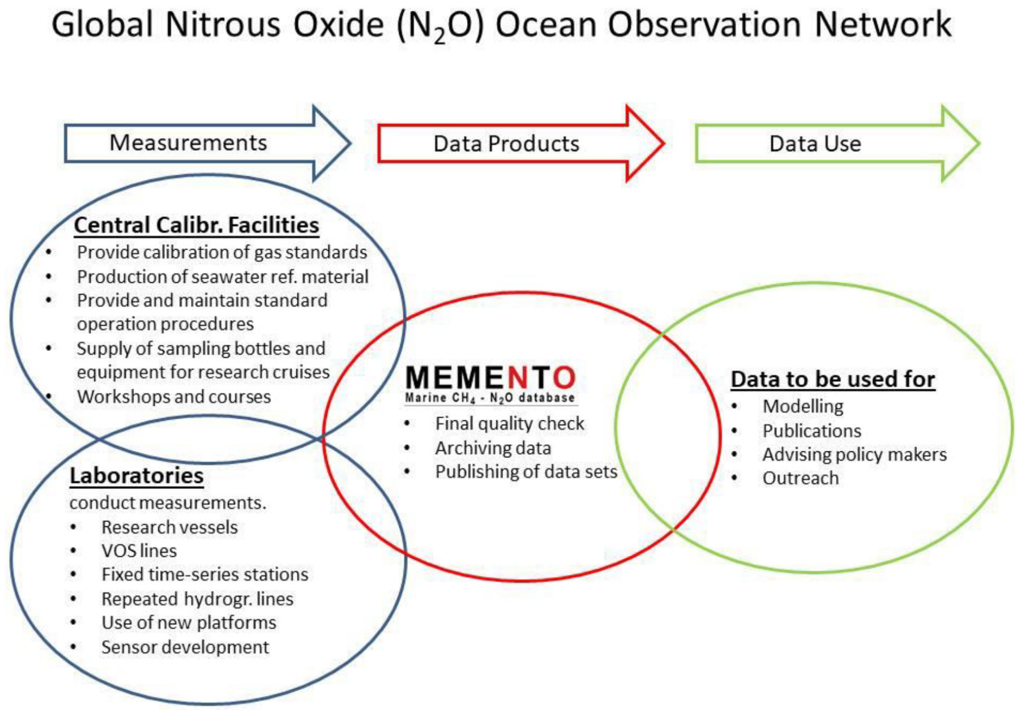

FIGURE 3 | Proposed scheme for the Global N_2O Ocean Observation Network. MEMENTO stands for "MarinE MethanE and NiTrous Oxide" database: https://memento.geomar.de/de.

N_2O variability in the ocean interior, thus forming an important N2O-ON collaborative activity. N2O-ON will also encourage the regular monitoring of N_2O in shelf areas and estuaries, which are prone to changes in redox-sensitive biogeochemistry due to enhanced anthropogenic and climatic impacts. Such activities would ideally be managed by local oceanographic institutes and/or relevant universities.

Established N_2O time-series (see Section "VOS Lines") at fixed station sites need to be continued. N2O-ON will identify additional sites to be established in the EBUS off Oregon/California, Peru, Mauritania and Namibia, in the northeast Indian Ocean (Bay of Bengal), and at some strategic coastal and enclosed basin sites to form a comprehensive and coordinated network. In addition to being important N_2O sources to the atmosphere, these regions benefit from proximity to the necessary infrastructure provided by local/regional oceanographic institutes.

SUMMARY AND OUTLINE OF N_2O-ON

Surface N_2O concentration data can now be obtained with unprecedented precision. The inherent error in the CEAS technique is small relative to error in associated measurements (e.g., temperature correction to the seawater supply, non-steady state in the equilibration chamber, etc.). Even so, a harmonized data set requires a mechanism for inter-calibration, mutual agreement on metadata information and standard post-processing operations, as has been established for the global ocean surface CO_2 network SOCAT (Pfeil et al., 2013). Enhancing the accuracy and consistency of discrete dissolved N_2O concentration measurements requires the availability of liquid standards derived from strict preparation protocols, for example by the equilibration of seawater with air at known temperatures and salinity (Capelle et al., 2015; Wilson et al., 2018), or through the distribution of certified reference materials covering the range of concentrations expected in the oceanic environment (Wilson et al., 2018). The availability of a suitable reference material has been crucial in quantifying the oceanic carbon system (Dickson et al., 2007) with the required precision and accuracy to detect and evaluate long-term trends [e.g., (Müller J. D. et al., 2016)].

To improve and harmonize N_2O measurements in a changing ocean, we suggest establishing a Global N_2O Ocean Observation Network (N2O-ON) as outlined in **Figure 3**. In addition to exploiting existing oceanographic infrastructure (research vessels, VOS/repeat hydrographic lines etc.), we propose to establish central calibration facilities (CCF) in selected laboratories around the world to secure the comparability of N_2O measurements, and provide data sets with maximum accuracy. The CCF will: (1) enable the precise calibration of N_2O gas standards; (2) produce certified seawater reference material; (3) provide and maintain standard operating procedures for both surface and water column measurements; and (4) supply sampling bottles and equipment for research campaigns. Moreover, the N2O-ON calibration facilities will conduct regular internal comparison exercises to ensure long-term and high-level calibration performance. MEMENTO will archive all N_2O data and make them publicly available following stringent quality checks. MEMENTO will also publish the N_2O data sets with digital object identifiers (doi's) to ensure appropriate referencing and tracking. Final N2O-ON data products, such as global N_2O concentration maps, emissions, budgets and trends, will be used in modeling studies for projections of future trends in oceanic N_2O emissions and advising policy makers and global climate assessments (Ciais et al., 2013). We advocate the establishment of regular workshops and courses to support all of these activities and to train the additional next generation of researchers who will be required to help realize the goals of N2O-ON.

DATA AVAILABILITY

No datasets were generated or analyzed for this study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REVIEW
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Coastal Mooring Observing Networks and Their Data Products: Recommendations for the Next Decade

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Instrumented moorings (hereafter referred to as moorings), which are anchored buoys or an anchored configuration of instruments suspended in the water column, are highly valued for their ability to host a variety of interchangeable oceanographic and meteorological sensors. This flexibility makes them a useful technology for meeting end user and science-driven requirements. Overall, societal needs related to human health, safety, national security, and economic prosperity in coastal areas are met through the availability of continuous data from coastal moorings and other complementary observing platforms within the Earth-observing system. These data streams strengthen the quality and accuracy of data products that inform the marine transportation industry, the tourism industry, fisheries, the military, public health officials, coastal and emergency managers, educators, and research scientists, among many others. Therefore, it is critical to sustain existing observing system networks, especially during this time of extreme environmental variability and change. Existing fiscal and operational challenges affecting the sustainability of observing networks will likely continue into the next decade, threatening the quality of downstream data and information products – especially those used for long-term monitoring, planning, and decision-making. This paper describes the utility of coastal moorings as part of an integrated coastal observing system, with an emphasis on stakeholder engagement to inform observing requirements and to ensure data products are tailored to user needs. We provide 10 recommendations for optimizing moorings networks, and thus downstream data products, to guide regional planners, and network operators:

1. Develop strategies to increase investment in coastal mooring networks
2. Collect stakeholder priorities through targeted and continuous stakeholder engagements

3. Include complementary systems and emerging technologies in implementation planning activities
4. Expand and sustain water column ecosystem moorings in coastal locations
5. Coordinate with operators and data managers across geographic scales
6. Standardize and integrate data management best practices
7. Provide open access to data
8. Promote environmental health and operational safety stewardship and regulatory compliance
9. Develop coastal mooring observing network performance metrics
10. Routinely monitor and assess the design of coastal mooring networks

Keywords: coastal, mooring, buoy, ocean, data product, observing systems, user needs

INTRODUCTION

Human health, safety, and economic prosperity are tightly connected to the health and state of the ocean, particularly in coastal areas and major lakes. Coastal observations of physical, chemical, and biological variables provide the backbone of coastal intelligence, and contribute to evidence-based decisions in response to societal challenges such as food and water availability, energy security, and the development of sustainable economies. The societal benefits of ocean observations are interconnected at local, regional, national, and global scales, and these observations are indispensable tools for addressing and mitigating risks and producing skillful predictions, especially in coastal areas (Malone et al., 2014).

Observations from instrumented coastal moorings (hereafter referred to as "coastal moorings") are critical components of the Global Ocean Observing System (GOOS). Coastal moorings are valued for their ability to measure temporal variability through the collection of continuous oceanographic and meteorological data sets on appropriate time-space scales. These observations enable the assessment of environmental or ecosystem conditions and variability and the impact of events to coastal areas, which will then allow us to forecast, adapt to, and mitigate changes. Federal, tribal, state, academic, industry, and public stakeholders rely on this information for a wide range of applications, including shipping, fishing, tourism, energy generation, and scientific research.

Coastal moorings are anchored buoys or an anchored configuration of instruments suspended in the water column collecting near real-time or delayed mode atmospheric and/or oceanographic observations at one or more depths. The coastal area is from the head of tide out to the edge of the continental shelf. The ability to monitor in near real-time is essential for ocean state forecasts, as well as for the long-term maintenance of the monitoring systems. The moorings may have a surface expression such as an instrumented buoy (enabling near real-time transmission of data) or may be configured in buoyant suspension below the surface of the ocean (**Figure 1**). Some vertically profiling moorings have an instrument package that "crawls" up and down along the mooring line, which allows a single set of sensors to take measurements at multiple depths (McArthur et al., 2017). Only moorings intended for long-term monitoring are considered in scope, which includes seasonal and long-term research moorings as opposed to experimental or short-term project moorings.

This paper describes the utility of coastal moorings as part of an integrated coastal observing system (observations – data management – products), with an emphasis on stakeholder engagement to inform observing requirements and to ensure data products are tailored to user needs. Existing observing capabilities, plus recommendations for improved ecosystem monitoring from moorings are discussed, as well as network design considerations. The importance of data management standards, especially quality control, is emphasized as vital to the integration of moorings data with other observations. Finally, a sample of products are provided to demonstrate moorings data integrated with other observing system data to successfully deliver real-time or forecast information for public consumption. We conclude with recommendations toward sustained moorings networks that deliver continuous, high quality data in order to optimize downstream data products to meet stakeholder and science-driven needs.

Observations Collected by Moorings

Coastal moorings can provide systematic and simultaneous observations in the air, at the sea surface, and throughout the water column all the way to the seafloor. They can support complex payloads, allowing co-located measurements of many of the GOOS Essential Ocean Variables[1], and are relatively easy to upgrade and equip with additional sensors, especially as the adaptive management needs of mission requirements evolve (McArthur et al., 2017). Rather than list all of the variables an instrumented mooring is capable of measuring, it is simpler to categorize the moorings into common combinations of the ocean, meteorological, and biological variables selected to meet a primary mission requirement.

- **Physical Oceanographic moorings:** These moorings are used to monitor the physical environment of the water column, and the main measurements along an in-line

[1] www.goosocean.org/eov

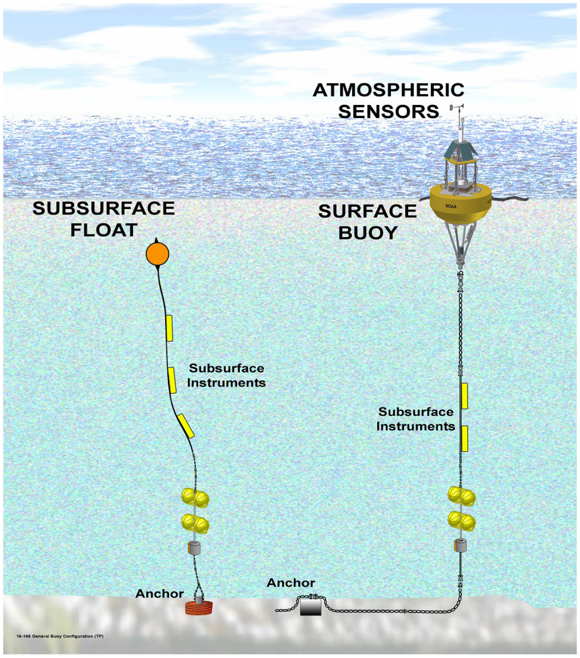

FIGURE 1 | Examples of coastal moorings. Coastal moorings may have a surface expression such as an instrumented data buoy or may be configured as an instrumented mooring in buoyant suspension below the surface of the ocean. Source: NOAA.

mooring consist of temperature, salinity and currents. Since the 1990s, mechanical single point rotary current meters have been replaced by acoustic Doppler current meters that can be point or profiling. A major use is to help calibrate and validate numerical hydrodynamic models.

- **Meteorological moorings:** These typically include measurements of the WMO essential variables for weather (wind speed and direction, air temperature, atmospheric pressure, and relative humidity) and GOOS physical EOVs at the surface (sea surface temperature, sea state). These measurements are critical for marine weather forecasting and navigation (WMO, 2015).
- **Wave moorings:** These moorings are primarily intended for monitoring surface GOOS physical EOVs (sea state, sea surface temperature, and/or surface currents). Thus, they are a type of physical oceanographic mooring that requires specialized, single-purposed platforms (e.g., Datawell buoys) to monitor wave height, period, and direction, and do not include instrumentation attached to the mooring line. Wave moorings are used for swell modeling, forecasting, and analysis of coastal environment data for use by coastal engineers, planners, managers, scientists, and mariners.
- **Ecosystem moorings:** These moorings measure a blend of GOOS EOVs across the physics, biogeochemistry, and biology and ecosystems categories, depending on their application, but always include at least one biological EOV. Surface observations are used for monitoring community structure and changes, detecting harmful algal blooms (HABs), and observing water quality. Subsurface observations are used to examine the water column structure to assess ecosystem characteristics. Physical, chemical and biological variables are often monitored simultaneously in time and space on these moorings.

Existing Networks of Coastal Moorings

Coastal moorings networks are operated and maintained by several countries around the world to meet local, regional, or national stakeholder observing requirements and scientific research needs. The Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) Data Buoy Cooperation Panel (DBCP), coordinates the use of over 400 of these moorings, and ensures the meteorological and oceanographic data are available in real-time (**Figure 2**) to support global forecasts of weather and ocean conditions. The DBCP inventory relies on meteorological and ocean observations delivered to and accepted by the World Meteorological Organization (WMO) Global Telecommunication System (GTS), therefore does not provide an exhaustive inventory of global coastal moorings (especially ecosystem moorings); however, it does illustrate the breadth of meteorological and ocean observing from coastal moorings.

A small selection of the many countries operating coastal moorings networks, who also contribute to the DBCP are:

The United States (US): About 370 moorings intended for long-term operations are deployed around the US coasts (including Pacific and Caribbean islands) and in the Great Lakes. Most notably, the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC)[2] operates 106 meteorological moorings for operational forecasting, warnings and atmospheric models, scientific and research programs, and emergency response to chemical spills. The US Army Corps of Engineers (USACE) Coastal Data Information Program (CDIP) network[3] of about 70 wave moorings are used by coastal engineers and planners, scientists, mariners, and recreational users. Almost half (145) of the US coastal moorings are operated by nonfederal groups that are part of (or partner with) the 11 US Integrated Ocean Observing System (IOOS) Regional Associations (RAs)[4]. The RAs are the regional component of the US IOOS[5], and provide integrated observations and data products in support of local stakeholders and scientific needs.

Canada: Canada's Weather Buoy Network[6] consists of 40 meteorological moorings deployed in coastal waters on each coast, as well as the Great Lakes and other major Canadian waterways. Real-time meteorological and

[2]https://www.ndbc.noaa.gov/
[3]http://cdip.ucsd.edu/
[4]http://www.ioosassociation.org/
[5]https://ioos.noaa.gov/
[6]https://www.canada.ca/en/environment-climate-change/services/general-marine-weather-information/observations/buoy.html

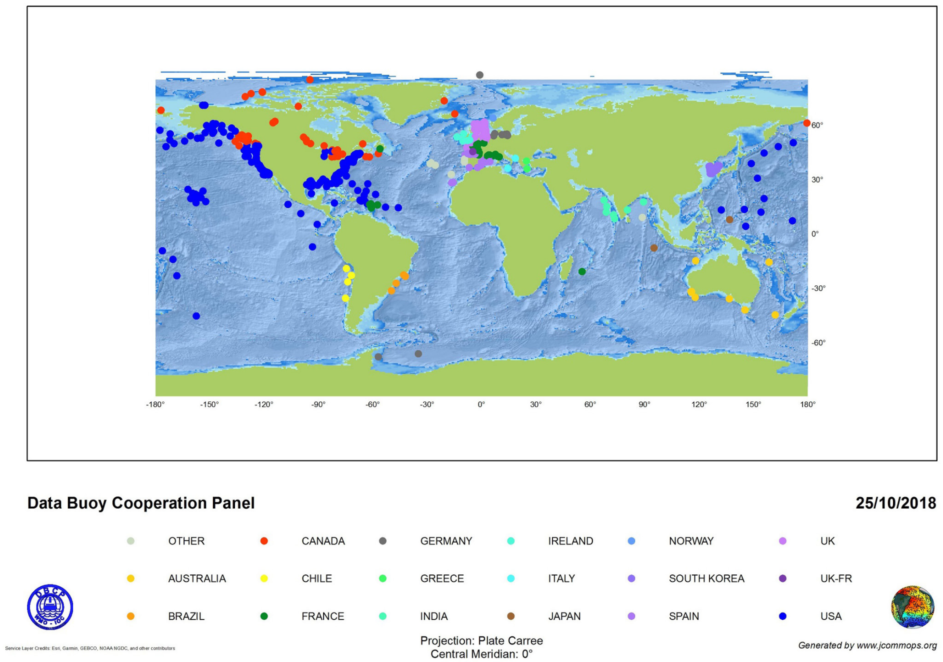

FIGURE 2 | Operational coastal moorings that are coordinated by the Data Buoy Cooperation Panel, as of October 2018. Source: JCOMMOPS.

oceanographic observations are delivered to and are managed by Environment Canada. The network provides mariners early detection and warning of incoming severe storms. At inshore locations, 20 of the 40 moorings are deployed seasonally during ice-free periods.

Australia: The Integrated Marine Observing System (IMOS)[7] operates a network of 7 National Reference Stations, which include vessel-based biogeochemical water column sampling (Lynch et al., 2014), as well as ocean acidification moorings, acoustic observatories, and regional arrays of over 30 moorings across the continental shelf. IMOS observations are guided by science planning undertaken collaboratively across the regional nodes of the Australian marine and climate science community with input from government, industry and other stakeholders. Observations are primarily used for studying ocean acidification and climate impacts to marine ecosystems. Outside of IMOS, Australian state governments operate coastal wave buoy networks in support of wave forecasts and maritime safety.

The United Kingdom (UK): The UK Met Office operates three coastal meteorological moorings that are part of the Marine Automatic Weather Stations (MAWS) network[8] of moorings and shore stations. Meteorological and wave observations are used for weather forecasting and real-time monitoring, climate studies, and ground-truth for satellite calibrations.

India: The Earth System Science and National Institute of Ocean Technology operates physical oceanographic and meteorological moorings for weather forecasting and climate research, among other applications, to understand and predict the Indian monsoon, tropical cyclone impacts, and air-sea interactions. Venkatesan et al. (2016) provides a detailed overview.

Ireland: The Marine Institute in collaboration with the Met Éireann and the UK Met Office operates the Irish Weather Buoy Network[9], five meteorological buoys around the Ireland coast that collect real-time meteorological and wave observations. The network is used to support maritime safety, as well as improvements in weather forecasts. Data are used for gale and swell warnings, search and rescue, validation of operational models, and research. The Marine Institute also operates four real-time wave buoys at two offshore test sites in support of marine renewable energy needs and climate research.

Spain: The Puertos del Estado operates about 15 coastal moorings as part of their coastal network[10]. These are mainly deployed in or near ports, primarily to provide real-time meteorological and wave data to support safe and efficient navigation, and for validation of operational wave models. Spain's port systems are closely tied to their economy, and the real-time weather and ocean information is vital to port safety and operations (Puertos del Estado and Ministerio de Fomento, 2015).

[7] http://imos.org.au/facilities/nationalmooringnetwork/

[8] https://www.canada.ca/en/environment-climate-change/services/general-marine-weather-information/observations/buoy.html

[9] http://www.marine.ie/Home/site-area/data-services/real-time-observations/real-time-observations

[10] http://www.puertos.es/en-us/oceanografia/Pages/portus.aspx

The Republic of Korea: The Korea Meteorological Administration operates a network of eight meteorological moorings located around the Korean peninsula[11]. These moorings measure wave observations for maritime safety and weather forecasting.

The abundance of global ecosystem moorings networks are not well-captured, and ecosystem moorings are likely scarcer than meteorological or wave moorings, given higher costs and/or feasibility of deploying newer sensor technologies on moorings. In the US, only about 10% of the 370 federal and nonfederal coastal moorings measure a combination of variables necessary for basic ecosystem monitoring. Specifically, physical variables like temperature and salinity measured at multiple depths and biogeochemical variables like oxygen and chlorophyll measured at least at one depth within the water column (McArthur et al., 2017). This subsurface coverage is critical for monitoring chemical and biological conditions and processes in the coastal ocean. Some of these moorings are part of the US Ocean Observatories Initiative[12] (OOI), which is an integrated infrastructure program for long-term physical, biogeochemical and ecological monitoring to inform research on climate change, ecosystem variability, ocean acidification, and carbon cycling. Similarly, long-term ecosystem moorings are included in the European Multidisciplinary Seafloor and water column Observatory (EMSO)[13], which is a research infrastructure consortium of regional mooring facilities in France, Greece, Ireland, Italy, Portugal, Romania, Spain, and United Kingdom intended for sustained, real-time monitoring. Beyond ocean observatories, sustained coastal ecosystem moorings are rare in observing networks.

COASTAL MOORINGS DATA COLLECTION

The Framework for Ocean Observing discusses a systems engineering approach toward a global sustained ocean observations network that integrates new biogeochemical, ecosystem, and physical observations while sustaining present observations without necessarily deploying new platforms (Lindstrom et al., 2012). The structure of the Framework for Ocean Observing consists of a feedback loop between science-driven requirements and observing system outputs (**Figure 3**). The process of determining what EOVs to measure and how begins and ends with stakeholder input. Once those requirements are gathered and EOVs are identified, a technology is then selected to measure those variables. Data are assembled, products are developed and distributed, and continued stakeholder engagement determines how the data collection process and/or products might need to change or evolve. Coastal mooring data collection requirements, therefore, hinge on stakeholder needs (both end users and intermediaries who develop value-added products) and engagement strategies to inform observing requirements. They also hinge on the state of sensor technologies for newer EOVs that are being implemented, such as biology and ecosystem variables.

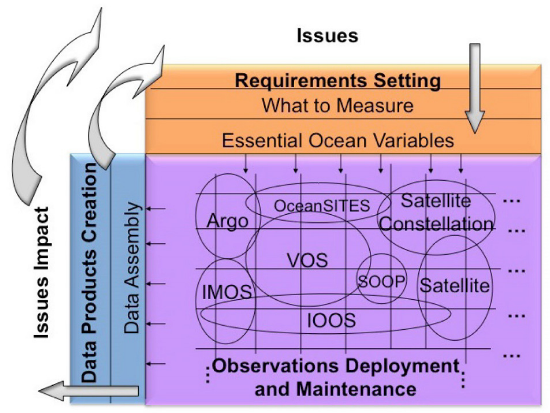

FIGURE 3 | The Structure of the Framework for Ocean Observing. Source: Lindstrom et al. (2012).

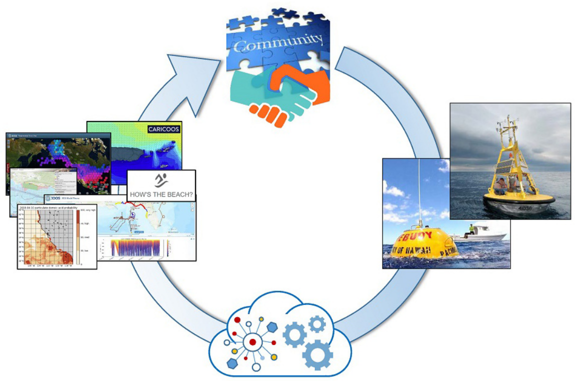

FIGURE 4 | The process by which IOOS RAs produce quality information products based on ocean observations to meet stakeholder needs. The process begins with stakeholder outreach discussions to determine what variables and measuring technologies are needed. Data are ingested into RA systems where they are quality controlled and distributed through regional portals and data access services. Data products developed by the RAs are tuned to stakeholder needs, and the RAs receive feedback through continued stakeholder engagements. Wave buoy source: Pacific Islands Ocean Observing System (PacIOOS); Meteorological buoy source: NOAA.

Stakeholder Engagement

There are numerous and diverse stakeholders of coastal mooring data representing federal, state, industry, academic, tribal, and other public groups. Stakeholder engagement across these groups is critical for successful partnering, stakeholder identification, and network change management solutions. For operators and data providers to fully capture and understand user requirements, stakeholders must be engaged throughout the lifecycle of the deployed technology and the downstream data produced. The US IOOS RAs excel at this continuous engagement, through

[11]https://web.kma.go.kr/eng/biz/observation_07.jsp
[12]https://oceanobservatories.org/
[13]http://emso.eu/

annual meetings, workshops, and through their organizational structures, which lend to close connectivity with researchers and coastal communities. Their process (**Figure 4**) mirrors the approach recommended by the Framework for Ocean Observing, and has been successful for connecting ocean observations and information products to societal needs. The US Pacific Islands Ocean Observing System (PacIOOS) stakeholder-driven approach toward prioritization and strategic planning serves as a model for ocean observing network operators – especially those operating with limited resources in a vast and diverse region. PacIOOS stakeholders have varying degrees of access to and/or understanding of ocean data. Therefore, PacIOOS categorizes stakeholders based on how much data they consume and their knowledge or understanding of ocean data, and this drives their level of engagement and outreach efforts, which then enables them to effectively identify and prioritize user needs (Iwamoto et al., 2016). Operators around the world should establish this type of strategic approach to effectively maximize stakeholder engagements.

Operational Observing Capabilities

Once stakeholder requirements are gathered, variables must be selected, though are constrained by the availability of measurement technologies. The GOOS categorizes ocean and atmospheric observations in terms of their readiness for operational capabilities (Nowlin et al., 2001; Nowlin and Malone, 2003). A summary of these are:

1. Research: Development of an observational/analysis technique within the ocean and meteorological community
2. Pilot Project: Community acceptance of the methodology gained
3. Pre-operational Projects: Use of the methods and data
4. Observing System: Incorporation of the methods and data into an operational framework with sustained support and sustained use to meet societal objectives (Nowlin et al., 2001; Nowlin and Malone, 2003).

Physical EOVs are routinely measured at physical oceanographic, meteorological and wave moorings in ocean observing systems like the US NDBC and CDIP networks, and the IMOS network. These measured parameters and methods have been incorporated into an operational framework with sustained support and sustained use to meet societal objectives; however, biogeochemical measurements are not as mature. Biogeochemical instrumentation ranges in readiness for operational capabilities from category one (Research) to category three (Pre-operational Projects). With the exception of chlorophyll, very few biological variables are operational. Activities toward implementing biological essential ocean variables are ongoing, and are coordinated by the GOOS Biology and Ecosystem Panel (GOOS BioEco).

In response to a need for defined ecosystem observing capabilities on moorings, the US Alliance for Coastal Technologies[14] (ACT) coordinated a National Coastal Ecosystem Moorings Workshop to identify a combination of required variables for robust ecosystem monitoring, depending on the environmental process being measured. Participants focused on identification of stakeholders and use cases of coastal marine ecosystem mooring data in the US, then discussed challenges and technical requirements, and concluded with recommended configurations of an ecosystem mooring:

1. *A **backbone*** of core biogeochemical and physical measurements, which are ancillary to ecosystem observations and which all sites should collect and have in common: temperature and salinity at the surface and subsurface to resolve relevant stratification; dissolved oxygen (at least subsurface); pressure or depth where the sensors are; and chlorophyll/backscatter in the surface layer. This backbone of core biogeochemical and physical measurements informs issues like hypoxia as well as bloom dynamics. It also gives insights into upwelling and thus is important to inform ecosystem processes.
2. A ***recommended suite*** of measurements includes the backbone measurements described above in addition to all or a subset of the following, based on the regional needs and applications: pH/pCO_2 (at surface both are recommended, but subsurface pH only is acceptable); color dissolved organic matter (CDOM), nitrate, current velocity, meteorological variables, passive bioacoustics (including fish tag receivers), active bioacoustics, and photosynthetically active radiation (PAR). This suite of measurements will help uncover processes driving ecosystem variation, advance direct measurement of biology, help validate ecosystem models for target species and protected species, and may also lead to understanding and predictability of events.
3. A ***high-capability suite*** consists of variables measured by technologies that are available but costly, and therefore recommended at a subset of sentinel or demonstration sites. This includes the backbone measurements plus a subset of the following, based on regional needs and applications: carbon system variables (beyond just pH and CO_2), CDOM, nutrients, current velocity, meteorological variables, passive bioacoustics, active bioacoustics, and PAR, with spectral, genomic sensors and imaging sensors. This high-capability suite enables real-time detection of toxins, food-web members (plankton and fish) and productivity for informing fisheries management (McManus et al., 2018).

The recommended suite in particular should be used to guide regional planning and should be adopted by operators across the GOOS.

Supplemental Sampling

A regime for vessel-based supplementary biogeochemical sampling and laboratory analysis is recommended to add value to ecosystem moorings measurements. Supplemental measurements also improve the quality of moored observations. In particular, due to the significant drift and bio-fouling of optical sensors, additional conductivity, temperature depth (CTD) casts or water samples should be taken regularly (e.g.,

[14]http://www.act-us.info

at each mooring service). The data can be used to calibrate instrument data throughout its deployment. This requires a systematic comparison and correction of the datasets.

The CTD or water samples can be taken throughout the whole water column to give more detail on stratification and mixing depths and conditions. For example, physical collection and analysis of nutrients, pigments, plankton and microbial sampling can describe the biological community structure at a higher taxonomic resolution for ecosystem assessment, and can be used as inputs to nutrient-phytoplankton-zooplankton (NPZ) models, and describe seasonality and interannual biological community responses to physical drivers. This collection and analysis can also lead to better understanding of biological responses and higher-resolution data, which is not yet available through sensor deployment. Species-level biological data is a future capability for *in situ* equipment on moorings, and microscopic analysis of physical samples remain the best method to get detailed information on community structures. Thompson et al. (2009) demonstrates that long-term monthly sampling at three moorings in Australia is an adequate sampling frequency to detect trends in parameters, such as water temperature, affecting nutrients and phytoplankton community structures. However, the temporal resolution required to resolve trends in plankton dynamics varies depending on the ecosystem and on the types of functional plankton groups present. Many studies have shown the inadequacy of monthly sampling when it comes to plankton dynamics. Thus, there is a critical need for sustained, continuous, high resolution observations of the plankton.

Other types of recommended supplemental sampling include:

- CTD and Secchi disc – to ground truth sensors, provide a complete water column profile, and clarify the degree of mixing or stratification.
- Variables for carbon monitoring, total organic carbon, total alkalinity, salinity, measurements important to ocean acidification.
- Suspended particulates, which are useful for validation of satellite retrieved estimates of total suspended matter and chlorophyll *a* concentrations.

Coastal Mooring Network Design and Configuration

The location of mooring arrays have traditionally used advice from experts or those that are aware of certain phenomena that need to be better understood. With long term observations it is important to also ensure that the mooring observations are of value over as wide area as possible so they are useful to as many people as possible.

In order to palliate the spatial limitations of moored observations, clusters and arrays are necessary, and complementary platforms are recommended. For example, while a single temperature mooring provides climate change baselines, a single velocity mooring is of less value; however, an array of just three velocity and or temperature moorings (e.g., across the shelf) provides significantly more detail. We recommend an initial study prior to the design of any observational system to provide the spatial context to identify the optimal locations and recommended variables to measure (Roughan et al., 2013). This is best conducted from observational and modeling studies. Where a surface expression is possible, we also recommend extending the mooring with near surface observations, and a meteorological station, including critical measurements for satellite validation, and meteorological information to enable a better understanding of the local dynamical drivers.

To ensure the most economic spread of observations, International observational programs have been assessed using Observation System Simulation Experiments (OSSE) in order to optimize temporal and spatial coverage when designing the array (Oke et al., 2015). Observation System Simulation Experiments use a model simulation to measure the effectiveness of observation techniques and observation locations needed to examine the state or phenomena of interest. Oke and Sakov (2012) used a model hindcast to determine how well the IMOS National Reference Stations monitor the shelf circulation, which identified several gaps around Australia. OSSEs can also use other spatial observations such as satellite derived chlorophyll-a to determine the footprint of existing observational arrays. This technique was applied to assess the value of the IMOS National Reference Stations and resulted in a re-design of the network (Jones et al., 2015). As another example, a wave model hindcast can be used to look at spatial coherence of the wave field around Australia to help identify gaps in the wave buoy data network. This has led to the prioritization of those locations for any expansion (Greenslade et al., 2018).

AN INTEGRATED SYSTEM

In the coastal ocean, physical and biogeochemical processes occur continuously over time and vary on smaller time-space scales than in the open ocean. Moored observations allow a good representation of temporal variability through the water column, with *in situ* measurements often every few minutes, at fine (cm–m) vertical resolution. Provided we succeed at sustaining coastal mooring sites over decades (e.g., off Sydney and Tasmania, Roughan et al., 2013), these observations allow us to investigate a range of temporal scales from turbulent mixing to inter-annual climate variability (Ruhl et al., 2011) at the mooring site.

Spatial representation is however an issue with fixed-point systems. Integration with data from other platforms is critical to complement moored observations in space over larger areas. For instance, satellite temperature, ocean color or altimetry observations, as well as coastal High Frequency Radars (Archer et al., 2017) can be used to provide a horizontal spatial context (at the surface) and identify spatial scales of variability, or how far from the mooring location the ocean variables are correlated. Moreover, moored data can be used to provide information on de-correlation timescales for satellite data, which is useful for gap filling (Lee et al., 2018) and validate radar observations (Mantovanelli et al., 2017; Wyatt et al., 2017).

Autonomous ocean gliders provide observations with high vertical resolution, and reasonable spatial coverage. Sensors for parameters typically include; temperature, salinity, and other biogeochemical variables such as chlorophyll fluorescence, light and dissolved oxygen. With sufficient data de-correlation length scales can be estimated throughout the water column (Todd et al., 2013; Schaeffer et al., 2016). When combined with HF radar data and moored observations, a comprehensive three-dimensional picture emerges of the coastal ocean, e.g., off the coast of SE Australia (Roughan et al., 2015; Schaeffer et al., 2017).

Finally, moorings data can complement vessel-based hydrographic sampling, giving temporal context to vertical profile data. For example, off the coast of Sydney, Australia, a dataset of more than 65 years of hydrographic sampling was augmented with a thermistor string approximately 10 years ago, thereby adding significant value to both datasets over many timescales (Schaeffer and Roughan, 2017). Richardson et al. (2015) used the IMOS mooring arrays with the complementary vessel-based sampling information to complete an assessment of Australia's oceans using plankton data as indicators of change to link science and policy in one document. Again, this shows a significant added value to both datasets when used in conjunction with each other.

By-products from complementary platforms can also help place the moored observations in context. Local upwelling indices (e.g., Alvarez et al., 2008 based on nearby meteorological station, satellite scatterometers or atmospheric models), and distance from the boundary current (when applicable, potentially calculated from satellite altimetry) provide valuable information on the main drivers of the local dynamics.

DATA MANAGEMENT

The quality and availability of observations from moorings are increasingly critical for developing data products that adequately meet user needs. Thus, continued emphasis is placed on adoption of and adherence to data management standards and provision of open access to observations. This includes robust metadata, implementation of quality control procedures (e.g., QARTOD – the Quality Assurance and quality control for Real-Time Oceanographic Data), and widespread use of data access services that enable automated discovery and access to global data sets. Adoption of these standards will also facilitate integration of moorings data with other complementary observing systems, increasing the production of multi-use data and information products that target a wide audience.

These standards will also facilitate use by the modeling community. Coastal moorings information is used to ensure the quality and accuracy of ocean models through cal/val and assimilation. Increasingly, operational models are becoming more commonplace and so near real-time data streams that undergo near real-time quality control are highly sought after to better assess model performance. This also requires uncertainty estimates of the data supplied. Therefore, these "model-ready" data, in easily accessed and ingested data formats, are increasingly vital.

Production

Along with the data itself, including detailed and consistent metadata and quality control information is crucial when generating datasets. A data producer should have all this information at hand, yet it is not always homogenous and available in a single place. For example, the Australian Ocean Data Network (AODN) and the Australian National Mooring Network (ANMN) have developed an imos-toolbox[15] to process data manually retrieved from long-term mooring sites. As shown in **Figure 5**, this toolbox can read the data from instrument files and the metadata from a deployment database in order to produce NetCDF files that include both data and metadata. In addition, the toolbox can perform pre-processing and quality control operations, and add the results to the NetCDF files. These files are compliant with the Climate and Forecast (CF) 1.6[16] and IMOS 1.4[17] conventions. The toolbox is operated by data producers since they have expertise over the data, metadata and quality control of this data. It produces consistent NetCDF files ready for ingestion by the AODN. This open source software can be adopted by any institution to process their moorings data.

Ingestion

With improved instrumentation and advancing technologies, the volume, variety and complexity of data from moorings (and other observing systems) is increasing. Data providers are also numerous and diverse. Data management systems need to be able to ingest data from all sources in a reliable and consistent way to ensure the safe archival and integrity of the data. They need to maintain accurate catalogs of metadata to enable data discovery and access services, reporting of data holdings, and preservation of data lineage, including metadata lineage. Systems also need to be able to handle real-time ingestion for real-time data access.

Some recommended solutions to these challenges for moorings operators to consider are:

- Automated systems, with human intervention limited to high-level monitoring and dealing with unexpected cases;
- Generic and extendable software infrastructure to accommodate a variety of data types/sources;
- Data providers follow standards and conventions (e.g., CF). Compliance is verified early in the ingestion workflow, and subsequently assumed;
- All operations are recorded and easily retrieved for data lineage reporting;
- "Serverless" architecture (e.g., AWS Batch) for modularity, scalability, and isolation of individual data streams.

As an example, some of these aspects have been incorporated into the data ingestion system being developed at the AODN (Hidas et al., 2016), which handles a broad range of ocean data from numerous providers around Australia. While the detailed ingestion workflow varies from one data source to the next, each can be broken down into a set of standard tasks, such as validation, processing, and publication (**Figure 6**). The behavior of each standard task can be customized, and additional steps can be included to extend their functionality. The system is

[15] https://github.com/aodn/imos-toolbox

[16] http://cfconventions.org/cf-conventions/v1.6.0/cf-conventions.html

[17] https://s3-ap-southeast-2.amazonaws.com/content.aodn.org.au/Documents/IMOS/Conventions/IMOS_NetCDF_Conventions.pdf

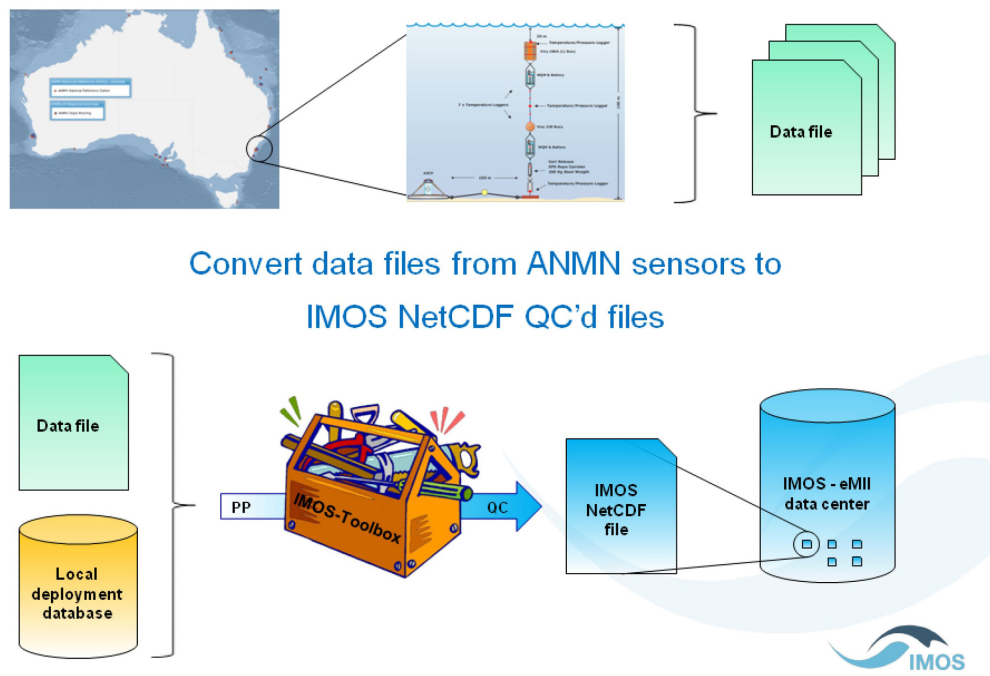

FIGURE 5 | IMOS moorings data production workflow. Source: the imos-toolbox GitHub wiki page.

implemented as an open-source Python package[18]. Although the package is designed for the AODN infrastructure, elements of it may be adapted, or used as a guide, by other operators to develop their ingestion systems.

Quality Control (QC)

Quality control processes and standards are critical for precise and accurate data, which in turn is critical for producing quality data products that serve stakeholder and societal needs. Data quality is the cornerstone of the US IOOS QARTOD project, which establishes data quality standards for IOOS core variables. Manuals that are relevant to coastal moorings operators are: passive acoustics, phytoplankton, dissolved nutrients, winds, *in situ* surface wave, ocean optics, *in situ* temperature and salinity, dissolved oxygen, and *in situ* currents data. A manual on pH is currently in development. These manuals detail QA/QC tests as well as information about the sensors and procedures used to measure the variables.

Successful QC requires convergence in standards and best practices in flag schemes, provenance, and algorithms and thresholds. Some challenges and/or considerations for the coming decade are:

- QC flag schemes: The QARTOD flag scheme (US IOOS, 2017) is based on the Intergovernmental Oceanographic Commission (IOC) 54:V3 primary level flag scheme (Intergovernmental Oceanographic Commission [IOC], 2013) while IMOS and many other institutions are still using an older IOC version used by ARGO.
- QC flags for provenance: users interested in QC are increasingly asking for information about which tests have passed/failed for a particular data sample, and not only the global result of all tests. CF allows for the description of such flags using bit field notation in flag_masks and flag_meanings attributes[19].
- QC tests algorithms and parameters: QARTOD defines automated and semi-automated QC tests for real-time observing. Many operators are struggling with assigning QC thresholds for parameters and tests. For example, the IMOS ANMN facility collects a lot of data (57 different instruments collecting more than 10 types of parameters at 137 sites), which makes QC operations a challenging activity in terms of human resources, so an automated approach[20] has been adopted. Any semi-automated QC test requiring defining thresholds/parameters that may be site and/or dataset dependent has been left optional.

While some QC tests can be automated, there is still a need for visual validation and manual QC to determine the validity of a flag, catch erroneous data that automated tests missed, and to ensure the automated tests are functioning properly. Dashboards and auto-generated reports can quickly identify sensor problems or determine the validity of a flag (**Figure 7**). To effectively use this type of dashboard, operators should document QC protocols describing which QC tests to use, how to parameterize them, and

[18]https://github.com/aodn/python-aodncore

[19]http://cfconventions.org/Data/cf-conventions/cf-conventions-1.7/cf-conventions.html#flags

[20]https://github.com/aodn/imos-toolbox/wiki/QCProcedures#moored-time-series

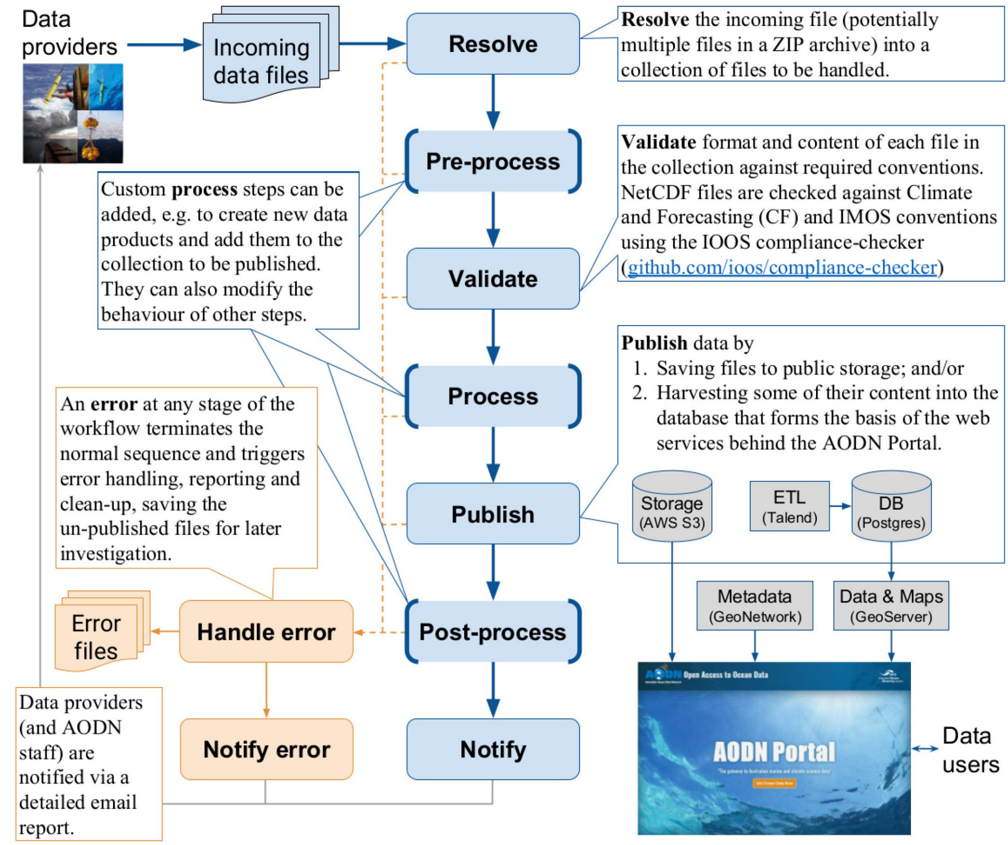

FIGURE 6 | Generic, customizable workflow of the AODN data ingestion system (Hidas et al., 2018).

what features to examine. For example, IMOS is in the process of documenting a QC protocol for temperature, salinity and pressure collected on moorings and using the imos-toolbox in order to achieve consistent QC across the national facility. This documentation is vital, especially if there is any divergence in QC practices. Standards and practices need to be described in order to potentially implement mapping between the different standards.

The QARTOD tests have been implemented by numerous operators around the world, and will continue to evolve over the next decade as technological capabilities evolve, particularly for biological variables. Furthermore, the GOOS EOVs will be reviewed to determine if any other variables are viable for a new QARTOD manual. It is highly recommended these tests continue to be adopted by coastal moorings operators for real-time observations. Other areas of QC within focus for the next 10 years that are applicable to moorings operators include:

- Automated cross-validation QC: QARTOD is already suggesting some tests in this field [e.g., the suggested Neighbor Test for real-time QC of *in situ* temperature and salinity data (US IOOS, 2016a)]. This effort should expand within QARTOD and these types of tests become elevated to "Required/Recommended."
- Use of artificial intelligence technologies (e.g., machine learning).
- Online collaborative (web 2.0) QC.

In addition to these focus areas, the International Quality controlled Ocean Database (IQuOD) group[21] is exploring both machine learning[22] and online collaborative QC approaches for profile data.

Data Curation

The sentiments expressed by the FAIR data principles (Findable, Accessible, Interoperable, and Reusable)[23] are readily applied to ocean observations collected on moorings. Data that have undergone quality control to published standards, with complete metadata records, must be preserved and archived with a data center for discovery and access. Properly curated datasets are vital for ongoing research that depends on high-quality ocean information. The ocean observing community need to not only ensure current and future efforts conform to the above standards, but identify and correct historical time-series data out of compliance with these standards.

As observing networks expand, and as programs also improve modeling capabilities, cyberinfrastructure components must

[21]http://www.iquod.org/
[22]https://github.com/IQuOD/machinelearn
[23]https://www.force11.org/group/fairgroup/fairprinciples

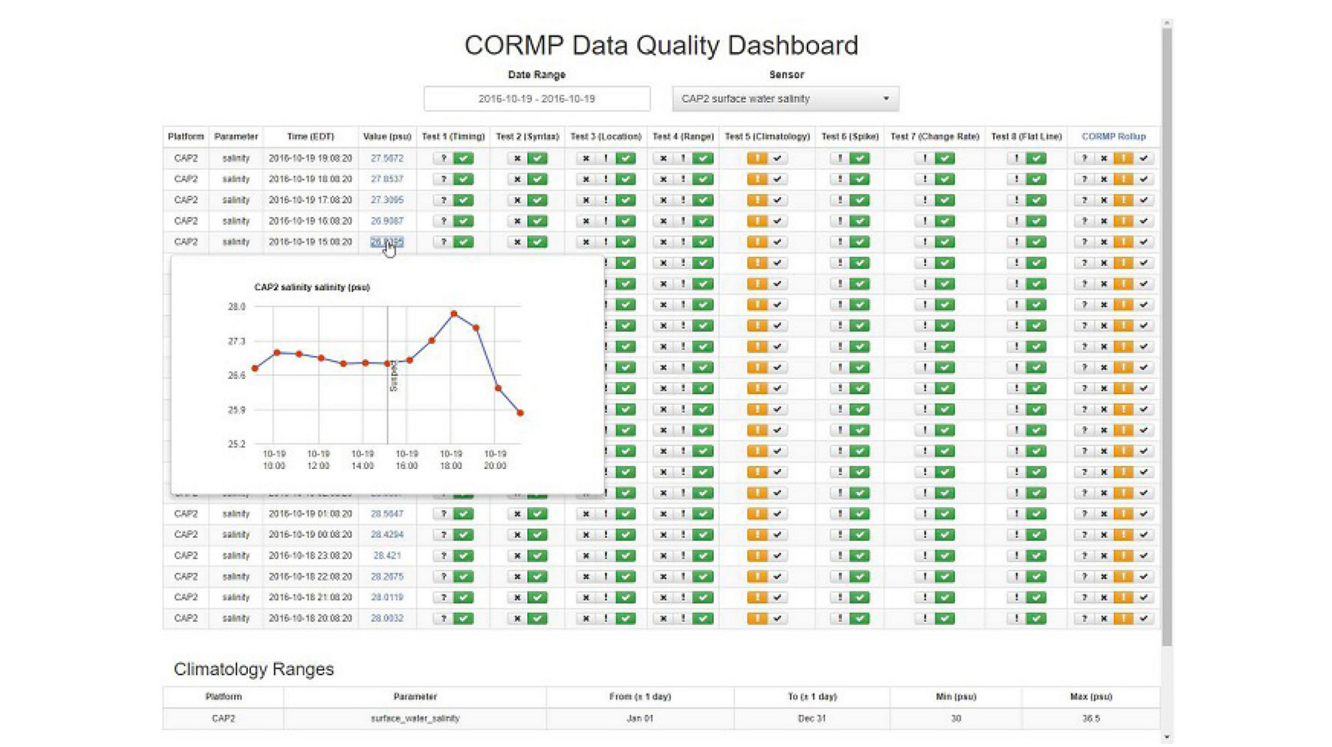

FIGURE 7 | The University of North Carolina-Wilmington Coastal Ocean Research and Monitoring Program (CORMP) recently implemented the Data Quality Dashboard and an auto-generated daily email with flags, which allowed operators to manually review flags to assess their validity, identify any trends, and accept or override flags. This example shows a flag triggered for coastal mooring salinity data after major rain event). Source: Jennifer Dorton, Southeast Coastal Ocean Observing Regional Association (SECOORA).

evolve to handle space requirements. Cloud services should be explored as a cyberinfrastructure solution to meet rising storage needs. For example, the AODN has adopted Amazon Web Services (AWS) for cloud storage and is also building its data delivery services on AWS. This allows them to meet rising storage requirements, plus AWS provides incremental backups and near 100% uptime for services.

Proper documentation of data management practices is essential, and these practices should be published. In the US, this is a NOAA requirement[24] for any funding recipients, and data management templates[25] are provided to guide operators, requiring descriptions of ingestion, QC, and archival of datasets. IODE Ocean Best Practices templates[26] are also publicly available, which some countries (e.g., Australia's IMOS) are in the process of implementing.

DATA PRODUCTS

Open data access is a guiding principle toward a successful integrated GOOS. The research community relies on data from all available sources to advance coastal modeling capabilities and studies focused on nearshore processes. Coastal moorings information is vital for these efforts, especially for real-time data assimilation systems that rely on the observations. Furthermore, openly accessible data bolsters the blue economy, which facilitates the development of value-added products across the Ocean Enterprise (profit and nonprofit groups in the private sector that engage in ocean observing and product development). In the US, more than 400 businesses across the Ocean Enterprise generate over $7 billion USD in revenue annually from ocean data and products (US IOOS, 2016b). Intermediaries tap into the enormous pool of ocean data to create value-added products that can be easily digested by a diverse audience. One area of focus is the development of mobile apps that turn open data into services. A recent "Big Button Ocean Data Challenge"[27] was sponsored by the XPrize Ocean Initiative on HeroX to motivate developers to harness ocean data to create mobile apps tailored to meet user needs (e.g., fishing and surfing conditions, marine navigation, educational tools, water quality status, etc.), targeting specific societal benefit areas. This challenge builds upon and advances the vision behind the New Blue Economy (Spinrad, 2016) – leveraging ocean data to further economic development – and also encourages coordination and collaboration between private industry developers and scientists. Mobile apps are an area of the new blue economy that is exploding, and over the

[24] http://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_212/212-15.html

[25] https://nosc.noaa.gov/EDMC/documents/EDMC-PD-DMP-2.0.1.pdf

[26] https://www.oceanbestpractices.net/handle/11329/400

[27] https://www.herox.com/bigoceanbutton

next 10 years will likely become a primary data product type for users across the world, which makes open data access all the more critical.

One way of promoting open access (beyond public data portals and data services) is ensuring observations are delivered to the GTS for operational ocean and climate forecast and analysis centers. The GTS is designed for international data exchange that enables development of early warnings and forecasts for hazardous events, as well as weather, water, and climate analyses and forecasts. Data are required in specific formats (e.g., BUFR), delivered through regional nodes. Unfortunately, the GTS was primarily designed with physical datasets in mind, whereas the ocean observing community (particularly modelers) have a growing need for biological datasets. BUFR templates are needed for this global distribution and are recommended as a focus for the coming decade.

Data Discovery and Access Requirements and Tools

Observing system programs require data systems that promote interoperability in order to enable user discovery and access of relevant data products. Different users have different needs and ways of interacting with data to advance research and product development. Uses range from simple summary plots to interactive plotting tools, from data download as simple CSV files to more complex formats such as netCDF and other machine-readable formats. Data required by a user is usually a subset and/or aggregation of available data collections, possibly from different sources and in different formats. Raw observation data required by a user may be large in volume but will often be processed into a much smaller final product for analysis. Furthermore, many "users" of observation data are actually software systems (e.g., models) that routinely and autonomously ingest large volumes of data. Users also require access to detailed data lineage information for transparency and repeatability.

Recommendations to improve delivery of moorings data are:

Standards and conventions for data discovery (e.g., ISO19115 metadata records), formats (e.g., CF), controlled vocabularies (e.g., the BODC Parameter Dictionary P01[28]), and access methods (e.g., Open Geospatial Consortium web services, see below) need to be more widely adopted and strictly followed. This will enable interoperability between distinct data access portals, and allow generic discovery, analysis and visualization tools to operate on all available data products. Coastal moorings datasets should be registered in data catalogs to promote discovery and access, following international standards and conventions.

Controlled vocabularies can be applied to a variety of key vocabularies like measured parameters, platforms and organizations, which can be defined with various levels of detail. These controlled vocabularies can drive faceted search so that portal users can discover data collections that are relevant to their needs without a prior knowledge of what is collected by an observing system.

Web services allow users (or software) to query, filter, transform, download or visualize data via web-based Application Programming Interfaces (API), without first downloading the entire data set. They also allow data *access* to be standardized, while allowing some flexibility in the format and storage method used for the underlying data. In particular, the Open Geospatial Consortium (OGC) defines the following standard services:

- Web Feature Service (WFS), for access to tabular data;
- Web Coverage Service (WCS), for access to multi-dimensional data;
- Web Map Service (WMS), visualizing spatial data as maps;
- Web Processing Service (WPS), allowing pre-defined operations to be applied to data by the server before downloading the result.

Metadata records are used to describe data collections in detail. They should also include information about relevant controlled vocabularies that are used, and online resources like access to files on servers and/or web services mentioned above.

Networks of data services Individual services can present data focused on specific regions or themes. If they are interoperable (based on the same standards), then broader services can easily integrate these to provide a more global view.

As an example, the infrastructure developed by the AODN (Hidas et al., 2016) uses WMS to display the spatial extent of data collections on a map, and WFS to provide access to one-dimensional data, or summary information on files containing multi-dimensional data. The open-source Open Geospatial Portal[29] provides a higher level, more user-friendly web interface to these base services, allowing users to discover, preview, subset, and download data collections. Collections from other organizations that have adopted the same infrastructure for their own data portals (such as the Australian Institute for Marine and Antarctic Studies[30]) are interoperable with, and easily imported into, the main AODN Portal (**Figure 8**). A key lesson learned from delivering moorings data via the AODN Portal is that, while it is able to display mooring sites as "dots on a map," this is not sufficient for complete discovery and visualization. The time and depth dimensions also need to be represented.

Our observation systems should include easy data visualization tools for end-users without the need for advanced programming skills. Interactive portals with a good graphical user interface are needed. If data can be provided in API format (application programming interface) then data can be readily ingested into a range of existing visualization platforms. ERDDAP is one solution toward this.

ERDDAP is a data server that was developed within NOAA to provide a consistent way for users (and machines) to access subsets of data in common formats. It is relatively low-effort

[28]https://www.bodc.ac.uk/resources/vocabularies/parameter_codes/

[29]https://github.com/aodn/aodn-portal

[30]https://data.imas.utas.edu.au/static/landing.html

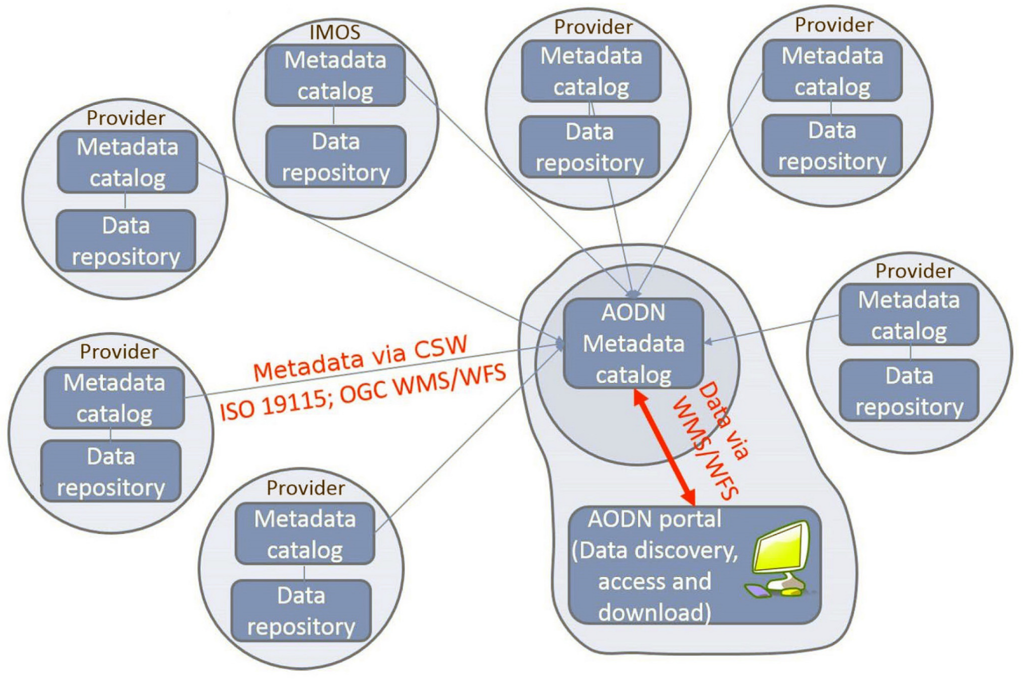

FIGURE 8 | The AODN portal as an example of a network of interoperable data services. Source: Hidas et al. (2016). Used under CC BY (http://creativecommons.org/licenses/by/4.0)/updated to remove the IMOS portal, which no longer exists.

to install and use, and it provides numerous benefits. ERDDAP can be installed alongside existing services and makes them interoperable, and can use those services as a data source, or it can directly access the data from source files. Ultimately, it serves as a broker between observing platforms and data users. Data that are produced in disparate formats are served in several different types of common formats, like.csv.html, ESRI.asc, Google Earth.kml, and netCDF; therefore, users do not need to convert datasets, they simply request the output format desired. A simple data access form within a web browser interface allows users to search, visualize, and download data, and it offers RESTful API services for automated machine-to-machine access.

ERDDAP has been gaining momentum among international operators and is being adopted to support data products. Over 70 institutions worldwide have installed ERDDAP, including Canada, Australia, France, Spain, and South Africa[31]. The US IOOS is also moving toward using ERDDAP as the standard source for the IOOS Data Catalog and other data products, and IOOS RAs will be adopting this service as a data broker for regional partner data. ERDDAP is highly recommended as a standardized data service that should be adopted by international data providers.

Societal Benefits and Stakeholders Who Rely on Data Products

The open availability of coastal mooring data has enabled scientific research, supported economic and social activities and critical government functions such the protection of life and property. Coastal mooring networks are also important economic elements of the Ocean Enterprise, as the businesses therein deliver products and services that enhance the Coastal Economy (US IOOS, 2016b). Coastal moorings and their data products are used for and/or support:

- **Discovery:** As newer technologies are developed and added to moorings (e.g., Environmental Sample Processors), discoveries are made particularly in the area of biology, and biodiversity.
- **Ecosystem Health and Biodiversity:** Information from coastal moorings enhances our understanding of processes related to ecosystem health, and changes in biodiversity. This helps to protect coastal populations and resources, including fisheries, aquaculture, and marine ecosystems.
- **Climate Variability and Change:** Climate-quality observations from coastal moorings enhances our ability to understand, assess, predict, mitigate, and adapt to climate variability and change. For example, observations that enable carbon cycle research, or examination of sea temperature variations to assess impacts on local fishing in a warming climate.
- **Water, Food, and Energy Security:** Coastal observations uncover impacts of ocean acidification, hypoxia, or invasive species on aquaculture, fishing, tribal sustenance, and local economies.
- **Pollution and Human Health:** Coastal moorings data are used to monitor and predict environmental factors and

[31] https://coastwatch.pfeg.noaa.gov/erddap/index.html

hazards affecting human health and well-being, such as HABs and toxins.

- **Hazards and Maritime Safety:** Real-time data from moorings leads to reduced loss of life, property, and ecosystem damage from natural and human-induced disasters, through improved marine forecasts and warnings, by improving the safety and efficiency of all forms of marine transportation.
- **Blue Economy:** Open access to moorings data allows intermediaries to make use of the data as an input to value-added information products (US IOOS, 2016b). Real-time observations and data products support Blue Economy sectors such as tourism, ocean renewable energy, biotechnology, shipping, offshore oil and gas, and fishing and aquaculture.

Data Products and User Needs

Over the next decade, end users increasingly require global access to data products and visualizations that are accurate, high quality, easily understandable, and continuously updated. When the data from coastal moorings are integrated, they contribute to information products that become powerful tools for monitoring and prediction. Furthermore, since mobile devices have become more prevalent, data product owners must consider these types of technologies as products are developed and tuned to user needs. Some network owners have created mobile-friendly versions of web-based products for visualization on a mobile device. For example, NDBC provides a separate "mobile access" webpage showing a text-only version of the data for display on a mobile device.

Coastal Mooring Data Products

Coastal mooring data are accessed daily by millions of national and international stakeholders, and are integrated into a variety of products and services. These stakeholders include a broad spectrum of federal, tribal, state, and local agencies, private industry, nonprofit organizations, and the public. One of the keys to sustaining quality ocean observations is to develop both products and tools that address the needs of end users and that become indispensable to users. Furthermore, targeted products should be developed to help end users understand the context of the observations. The following examples illustrate the types of products that rely on or use coastal moorings data to present information that meets science-driven or stakeholder needs. These examples are provided to motivate regional programs looking to hone or develop new products.

Most common are products that display real-time information of weather and ocean conditions, which is particularly critical to port and harbor authorities for safe marine navigation. For example, **Figure 9A** shows real-time data from coastal moorings that are used by port operators to assess current conditions experienced at the harbor mouth. In this case, the mooring instruments captured extreme winds during a storm, and **Figure 9B** shows the program leveraging social media to report those extreme measurements. Real-time data in ports and harbors are also used as boundary conditions for operational models. Together, the information from the models and the real-time data improve port and harbor authorities and commercial and recreational mariners' ability to navigate safely.

Other products integrate model output and observations in a map-based visualization to allow users to make decisions using complementary information. For example, the US Northwest Association of Networked Ocean Observing Systems (NANOOS) Visualization System (**Figure 10**) allows users to examine coastal mooring data alongside Regional Ocean Modeling System (ROMS) model output for sea surface temperature and currents. In **Figure 10**, the ROMS output is color-coded to temperatures where tuna are most likely to be found (red) versus not (blue), to help commercial and recreational fishers plan efficient outings.

The US Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) OceansMap portal (**Figure 11**) provides another type of map-based visualization that also enables interactive time-series comparisons between observations and model output, at the mooring location for a user-specified timeframe. This feature allows research scientists to assess model accuracy and perform model validation. Furthermore, in this region the product has been valuable to coastal engineers who require all available observations (gridded surface currents, *in situ* observations, remote sensing data) in a particular area to inform design criteria for offshore wind farms.

The IMOS OceanCurrent product (**Figure 12**) focuses on observations, and combines all available sources in a map-based visualization (satellite sea surface temperature, altimeter-derived currents, Argo profilers, Surface Velocity Program drifters, ocean surface radar, and mooring currents through the water column). This provides a variety of users (emergency managers, public health officials, forecast offices, oil spill responders, mariners, and educators) with an understanding of current oceanographic conditions, and an archive also allows users to go back and look at an event to help understand what oceanographic conditions were at the time.

Other products target environmental events, such as HABs or hypoxia events. A NANOOS "Real-time HABs" app (**Figure 13**) allows health officials, coastal and environmental managers, water treatment facility operators and the marine industries (among others) to track the movement of toxic algae and monitor conditions that may influence toxic blooms. The Real-Time HABs webpage where the app is hosted was created with manager input. In this product, the observations are measured by a new Environmental Sample Processor (ESP) attached to a mooring, which identifies the presence of organisms and/or biological toxins. These data inform a NOAA HAB Bulletin that is delivered to state and tribal resource managers. Resource managers rely on the ESP "...as a tool [that] should really help us understand what is going on in the off-shore and how it relates to what we are seeing near-shore..." (Dan Ayres, Washington Department of Fish and Wildlife).

Another example of a targeted product is the PacIOOS turbidity plume forecast (**Figure 14**), which is helps recreational users and water quality managers assess the presence of pollutants and contaminants in coastal waters. The turbidity data collected by coastal moorings in the vicinity feed a ROMS numerical model that calculates the advection and dispersion of the turbidity

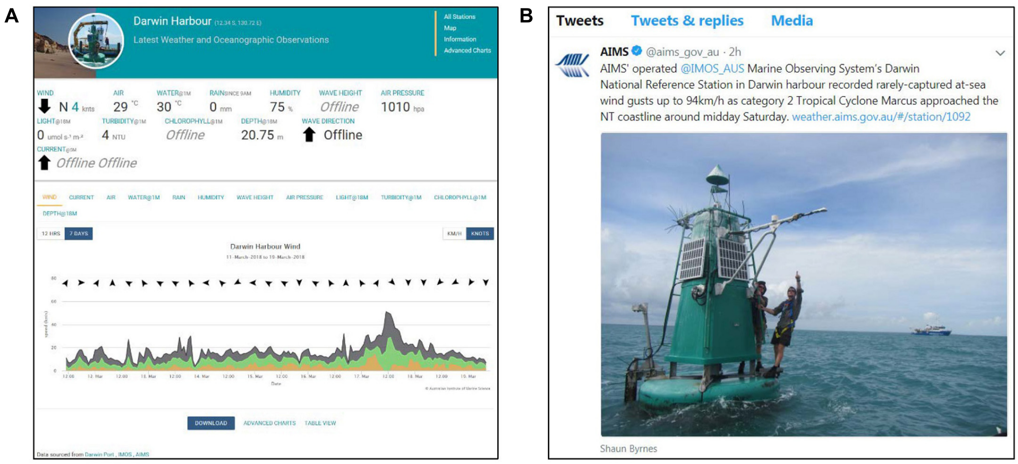

FIGURE 9 | Screenshot of the winds observed at the IMOS Darwin National Reference Station in Darwin Harbor, Northern Australia, during the passage of Tropical Cyclone Marcus in March 2018 **(A)** and a tweet generated to publicize the recorded event **(B)**. These data have improved the utility of a new East Arm wharf development where safe shipping movements have increased from 15 to 60% of the time. Source: IMOS.

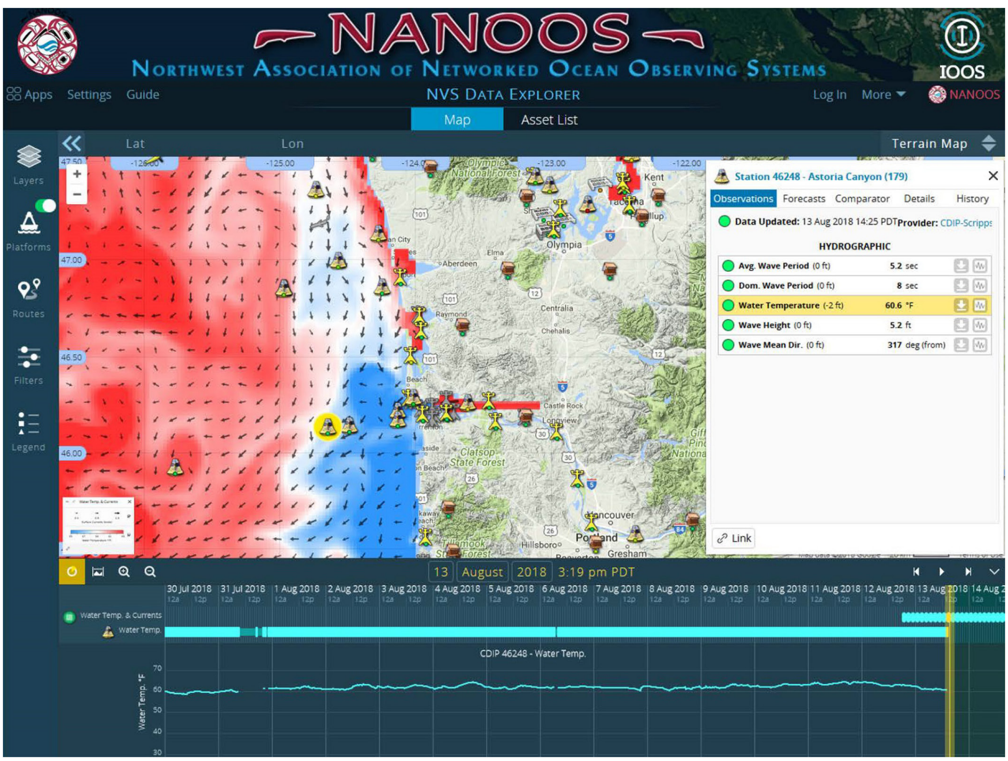

FIGURE 10 | The (NANOOS) Visualization System data portal for the US Pacific Northwest. Shown is Oregon State University Regional Ocean Modeling System (ROMS) model output for surface water temperature and currents, along with near real-time buoy data readings for several variables, including surface water temperature. Source: NANOOS (http://nvs.nanoos.org/Explorer).

plume over time. A near real-time map of freshwater movements during large storms identifies the location and movement of plumes of "brown-water."

Models are a vital tool for assessing and understanding coastal ecosystem changes, and are (as demonstrated) central to many data products. Modern ocean models require as much high-resolution data driven by long time-series measurements as possible to improve their accuracy. The fine scale (2 km) sea surface temperature atlas of the Australian regional seas (SSTARS) is a product that relied on moored sea surface

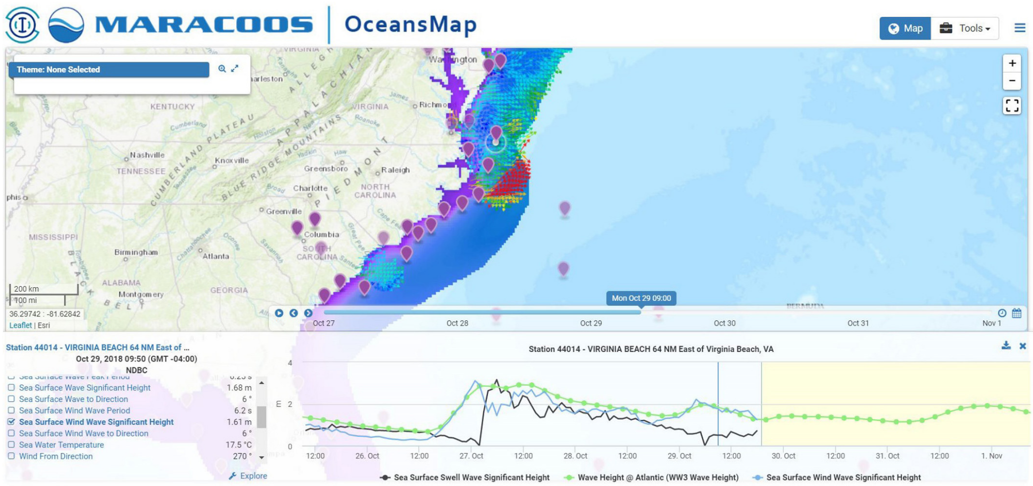

FIGURE 11 | NOAA Wave Watch 3 wave height (modeled), and High Frequency Radar surface currents data (observed) produced by MARACOOS, alongside real-time NDBC data (observed) from coastal moorings (purple markers). This product enables time-series comparisons at the coastal mooring location between modeled and observed variables. Source: MARACOOS (http://oceansmap.maracoos.org).

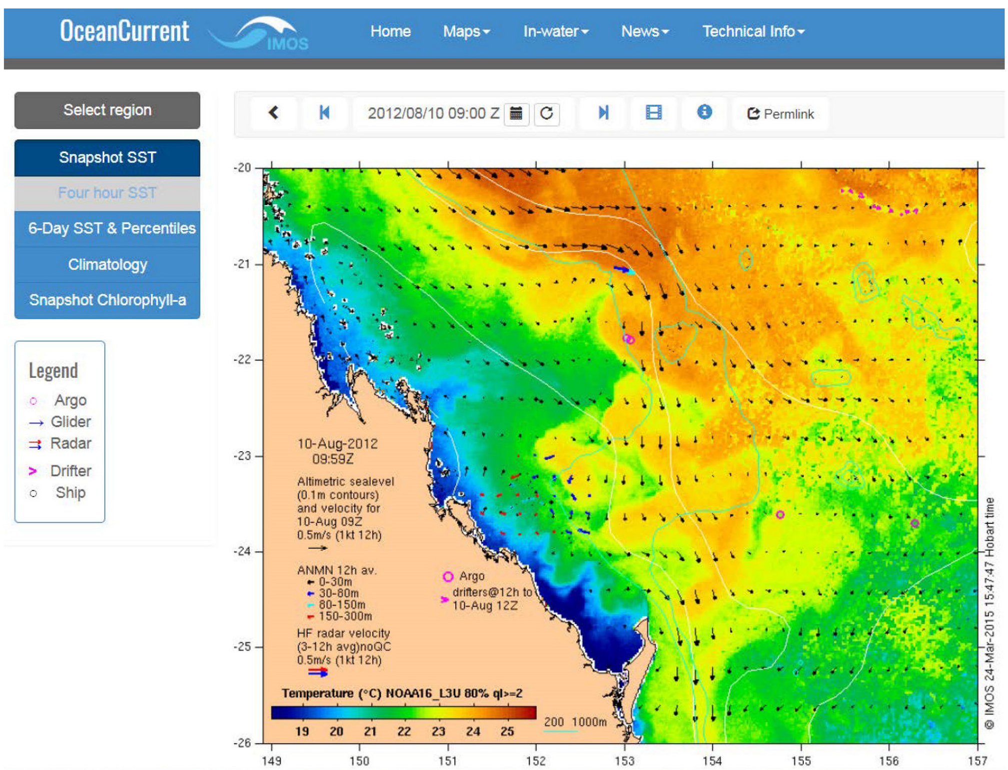

FIGURE 12 | Screen capture of the IMOS OceanCurrent map of the Southern Great Barrier Reef August 10, 2012. Source: IMOS (http://oceancurrent.imos.org.au/).

temperature observations for validating the remote-sensing SST data. The atlas covers the 25 years satellite record and is of significant duration to identify warming trends and spatial anomalies. This product is an excellent resource to regional modelers and will also inform research on ecosystem processes (Wijffels et al., 2018).

Many of the above examples are map-based visualizations; however, other value-added products derived from moorings observations are easy to construct and should be made available to facilitate real-time data uptake and to provide operational guidance in a decision-making timescale. For example, mean climatologies at different timescales (daily, monthly, seasonally,

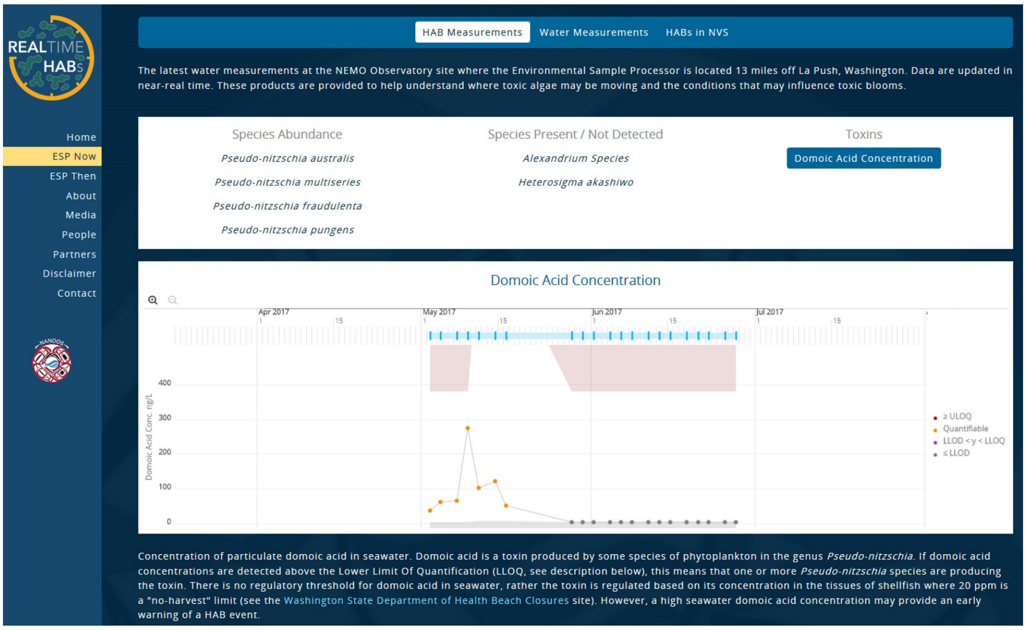

FIGURE 13 | Domoic Acid concentration from an ESP, deployed on a mooring near La Push, Washington. The ESP was deployed by University of Washington and NOAA Northwest Fisheries Science Center through US IOOS funding to NANOOS. Source: NANOOS (http://www.nanoos.org/products/habs/real-time/esp_now/hab_measurements.php).

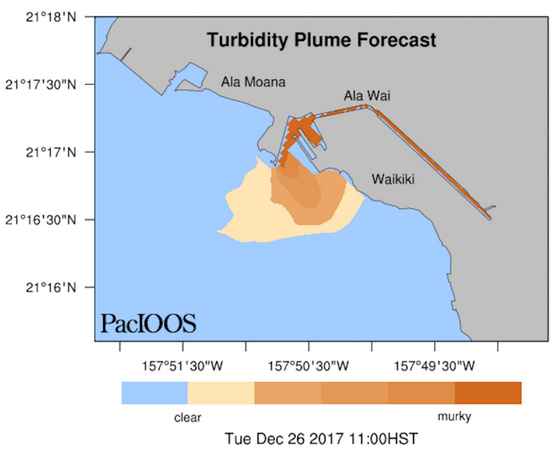

FIGURE 14 | An extreme high rainfall event in December 2017 caused a large turbidity plume off the coast of Waikîkî, Oahu, Hawai'i. This is one image from a longer animation of the time period produced by PacIOOS. The movement and lifespan of the turbidity plume through time depends on oceanic and atmospheric conditions. Source: PacIOOS (https://www.pacioos.hawaii.edu/water/model-plume-alawai).

and yearly) can uncover anomalous ocean conditions in ocean properties. And historic data can be useful for extracting statistics for a range of purposes including design criteria for structures (waves and currents), workability reports (wind, waves, currents) etc. thermal thresholds, for installation of new aquaculture facilities, etc. Percentiles of anomalies (**Figure 15**) can be used to identify extreme events such as marine heatwaves easily and routinely (Schaeffer and Roughan, 2017). Historical information is essential to construct the climatology, but real-time data is necessary if operational needs are to be met. For example, marine heatwaves (temperature extremes) are getting more frequent and intense (Oliver et al., 2018), but to date the majority of studies have focused on satellite data which only reveals the surface signature. However subsurface information is also important for marine industries such as the seafood sector (both wild caught and aquaculture) where animals live beneath the surface. Presently real-time monitoring of marine heatwaves is generally only possible at the surface due to a lack of long term *in situ* observations and climatologies of extremes, and real-time data streams.

Through the water column, gridded products for moored lines with different instruments should be provided to expand subsurface information, also specifying the criteria for vertical interpolation. Extra subsurface diagnostics could also be included in mooring products, such as the mixed layer depth, thermocline depth and Brunt–Väisälä frequency. Time-series of low-pass filtered and tidal-filtered dataset are also useful.

OPERATIONAL CHALLENGES

Coastal moorings operators may be distributed across the world, but experience many of the same challenges. The biggest shared challenge is sustaining the networks, particularly in the face of increasingly harsher climates/environments, rising operations and maintenance costs, vandalism, and/or reduced budgets. The National Coastal Ecosystem Moorings Workshop also identified some additional operational challenges that affect data quality and availability:

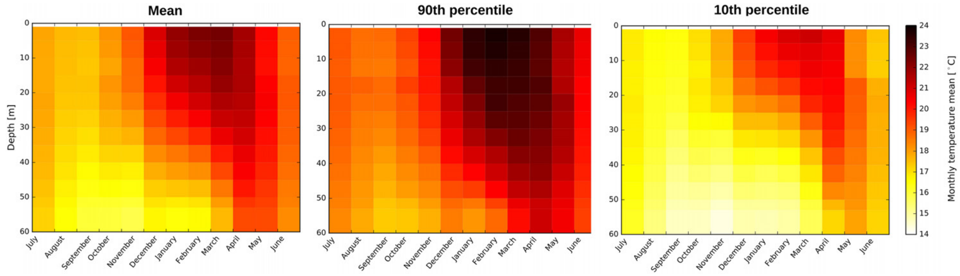

FIGURE 15 | Gridded monthly climatology for the mean, 90th and 10th percentiles of water temperature. Data are from a coastal mooring off Sydney Australia (ORS065) based on hourly observations from 1991 to 2016.

- Sensor calibration and accuracy estimates, which depend on the local laboratory facilities and the type of ship used for the mooring deployment.
- Biofouling, leading to higher maintenance costs. Sensors require more servicing with extended calibration intervals. For sustained measurements, the community needs field-proven methods to reduce biofouling.
- Ice cover, preventing year-round, real-time observations.
- Lack of new technologies on existing moorings. In some cases, there are no suitable sensors to measure the parameters required or these sensors are too expensive. Although, as the technology continues to evolve it is possible that these sensors may become more accessible due to reduced costs (McManus et al., 2018).

Over the past 20 years, instrumentation to measure biological and chemical properties in the ocean has seen rapid development, but still needs improvement. These sensors remain expensive and often require significant effort to maintain calibration, can be affected by biofouling and are often proxies for the desired observation, such as fluorometry in lieu of chlorophyll. These difficulties mean that such observations remain sparse and are often at risk of discontinuation in lean funding periods. This is a critical time for funders to invest in the development of these sensors in order to bring down the costs and make these sensors more affordable.

Resolving gaps in data products resulting from gaps in coastal measurements should be a focus for the coming decade. This is an issue primarily related to funding and technology limitations. For example, the following needs were identified in the US coastal regions:

- There are insufficient observations for HAB species and the detection of their toxins. Real-time, *in situ* data on HAB toxins are needed to validate and initialize toxicity forecast models. Seasonal but sustained observations of HAB species and toxins can provide valuable early warnings for potential coastal shellfish toxicity.
- Observations are needed to validate and initialize hypoxia forecast models.
- The local shellfish (e.g., lobster) harvest is impacted by low levels of dissolved oxygen and decreases in the benthic water temperature. More data are required to refine the models for improving commercial and recreational catch limits.
- Fisheries management would be improved by the wider use of acoustics for aggregation, fish spawning, and tracking. Acoustic monitoring baselines are necessary to understand biological impacts for fisheries management.
- An ice breaking buoy system should be developed to enable wider measurements in colder climates (McManus et al., 2018).

Coordinated Groups and Activities to Address Challenges

There are numerous coordinating groups and activities across the world at the regional, national, and international level. Here we provide a few examples of existing international and national coordination efforts underway to address technological challenges.

The DBCP develops best practices and other guidance to help mitigate some of these challenges, and coordinates activities through task teams. The DBCP Task Team on Moored Buoys coordinates across other JCOMM groups and national moorings operators to identify networks and underlying requirements, promote the development of multi-disciplinary mooring systems, leverage advances in operational and technological capabilities, and to monitor best practices documentation. Recently, the DBCP published an outreach strategy to address challenges related to vandalism. It describes a framework to promote public awareness of the value of data and services that instrumented buoys provide, as well as improved collaboration among operators to devise solutions for preventing vandalism (Joint Technical Commission for Oceanography Marine Meteorology [JCOMM] and Data Buoy Cooperation Panel [DBCP], 2017).

The European National Meteorological Services Network's (EuMetNet) E-SURFMAR program is another international coordination group and integrates surface marine observations and observing activities across Europe for operational weather and climate applications. Actions include coordinating deployments and maintenance activities through voluntary ships, shared equipment procurements, exchange of best practices among members and with other international groups, and data processing and delivery through portals and to the GTS.

At a national level, technological challenges are addressed through engagement and collaboration across societal sectors and across shared borders. For example the US ACT, which is funded through the US IOOS Office, is a partnership of research institutions, resource managers, and private sector companies, and transitions emerging technologies to operational use, engages technology users, developers and providers, identifies technology needs, and documents technology performance and potential. Recently, the ACT coordinated the National Ecosystem Moorings Workshop, which produced a recommendation on ecosystem mooring measurements from experts across public and private sectors. Another US coordination activity is the joint NOAA-Environment and Climate Change Canada (ECCC) pilot project that will focus on solutions for operating moorings in harsh climates. The project covers the development and testing of high-latitude batteries where limited sunlight in the winter months hampers the effectiveness of solar panels. The NDBC will install equipment at ECCC facilities in Ontario and Newfoundland, Canada and will monitor the performance of these two observing systems. Results will be shared at the conclusion of this project in 2020. Additionally, NOAA hosts an annual Emerging Technologies for Observations Workshop (ETW), aimed at identifying observing system technology to either replace existing capabilities at lower cost or fill current geographical gaps. The workshop sessions have focused on technologies the agency could incorporate within 3–5 years, and promoted collaboration between NOAA and private industry, academia, and other federal agencies (Goldstein et al., 2018).

In Australia, IMOS is responding to technological challenges by including assessment of new technology and developments into its decision-making process, following the GOOS Framework for Ocean Observing (Sloyan et al., 2018). When IMOS was established the emphasis was to deploy proven, reliable and robust observing platforms. Ten years later, it is clear that newer technologies need to be considered and integrated into the observing network without diminishing the continuity or quality of data streams. A new advisory mechanism to the IMOS Board is the Science and Technology Advisory Committee (STAC). This broadens the advice from regional science community nodes to ensure uptake of new technology is assessed and introduced in an appropriate manner.

It is clear that technological challenges are addressed at national and even regional levels, but it is unclear if solutions, methodologies, best practices, or lessons learned by those groups are effectively shared and distributed, for the benefit of other network operators. Therefore, we encourage continued involvement in and contribution to international groups like the DBCP, the E-SURFMAR, and the IODE Ocean Best Practices working group to ensure efficient distribution of project results and expertise, through this bottom-up approach.

VISION AND RECOMMENDATIONS

In the US, the loss of several critical moorings as a result of funding problems motivated the development of the *National Strategy for a Sustained Network of Coastal Moorings*. The vision described in the Strategy is applicable to coastal moorings networks around the world: "A sustainable national network of coastal moorings integrated with other environmental observing systems to improve management of resources, safety of life, protection of property, enhancement of the economy, protection of the environment, and science and information about the coastal system" (McArthur et al., 2017). The Strategy concludes with recommendations toward achieving this vision. We use those as a foundation to build upon, and pose the following recommendations for coastal moorings operators and institutions to consider for the following decade:

1. Develop strategies to increase investment in coastal mooring networks. Sustainable funding mechanisms must be identified to ensure and preserve the continuity and accuracy of the coastal environmental record by supporting capital purchases and through-life costs for a network of moorings. To do so, specific gaps must be targeted and presented to potential investors with a clear and compelling tie to stakeholder needs, particularly high-profile user needs, as well as a tie to data products that deteriorate as a result of observing gaps. Data denial exercises like Observing System Experiments could be used as a way to demonstrate the negative impacts of observing gaps on models, and thus products that rely on the observations and predictions.
2. Collect stakeholder priorities through targeted and continuous stakeholder engagements. A stakeholder engagement approach is essential to integrate the collective input of national and regional marine operators, federal and nonfederal moorings operators, and scientists. Stakeholder and scientific needs are the foundation for ocean observing activities, and drive technology and product requirements.
3. 2.1. Establish well-defined use cases to demonstrate and emphasize the value of data products that rely on coastal moorings. Connectivity to coastal communities and stakeholders enforces the value of observing systems by increasing dependency on data products. Improved data products and well-defined use cases will ensure greater understanding and engagement by stakeholders (McManus et al., 2018).
4. Include complementary systems and emerging technologies in coastal moorings implementation planning activities. When observations from the global earth-observing system are fully integrated, they provide a comprehensive picture of the environment, and greatly improve our ability to monitor and predict changes in weather, climate, ecosystems, natural resources and extreme events.
5. 3.1 Use OSSEs to inform optimal siting locations prior to designing a network as well as the initial study recommended in Roughan et al. (2013). Moorings site selection considerations must include proximity to ships, ports, and mooring groups for deployment and servicing, cross-calibration, and for providing complementary measurements (McManus et al., 2018). Complementary platforms (clusters and arrays) are recommended. Where possible, extend the mooring with near surface observations

and a meteorological station for satellite validation and to uncover local dynamic drivers.

6. 3.2 Invest in improvements to biological instrumentation to help reduce costs and complexity of operations so that they can be made suitable for deployment on coastal moorings (McManus et al., 2018).
7. Expand and sustain water column ecosystem moorings in coastal locations.
8. 4.1 Expand existing moorings with surface and subsurface measurements of physics, biogeochemistry, and biology and ecosystems variables, following the recommended configuration for coastal ecosystem moorings described in McManus et al. (2018).
9. 4.2 Conduct vessel-based, supplementary biogeochemical sampling and laboratory analysis to add value to these measurements.
10. Coordinate with operators and data managers across geographic scales. Coordinated engagements promote sharing of experiences, best practices, and advances in observations related to platforms, instrumentation, and data management and research applications, and lead to more efficient operations.
11. 5.1 Actively engage in coordination activities across local, regional, national, and international domains (e.g. E-SURFMAR, the Biogeochemical Argo Initiative, the IOOS QARTOD project, the DBCP Task Team on Data Management, and the IODE Ocean Best Practices working group).
12. 5.2 Coordinate maintenance activities with local ship operators (federal, state, university, private).
13. 5.3 Use collaborative platforms like Github to promote open communications among moorings operators, to assist with troubleshooting and other information exchange.
14. Standardize and integrate data management best practices. Compliance with data standards and best practices (e.g., data sharing policies, metadata standards, and QARTOD) promotes interoperability, and common web services and data formats.
    6.1 Document and publish data management practices to provide transparency on protocols applied to datasets. The IODE Ocean Best Practices templates are recommended.
    6.2 Implement ERDDAP and OGC standard web services (as applicable).
    6.3 Produce standardized calibration procedures utilizing national or regional calibration facilities, where possible. Produce and publish uncertainty estimates.
15. Provide open access to data. Publish data through products and services and deliver real-time data to the GTS for applicable variables. Contribute to other coordinated networks and systems that facilitate open data access for advancing studies on global issues (e.g., NOAA's open ocean moorings[32] contribute to the Global Ocean Acidification Observing Network[33]).
16. 7.1 Develop BUFR templates for biological variables to enable global exchange of real-time biological variables via the GTS.
    7.2 Expand the Ocean Data Interoperability Platform (ODIP)[34], the international (EU-USA-Australia) project, which contributes to removing barriers hindering effective data sharing across scientific domains and international boundaries.
17. Promote environmental health and operational safety stewardship and regulatory compliance. Check safety rules of the funding agencies, the universities, and any certifications or insurance of the vessels to be used. Written and regularly reviewed standard operating procedures and pre-deployment task risk analyses are also recommended (McManus et al., 2018).
18. Develop coastal mooring network performance metrics. Performance metrics should align with key stakeholder needs and promote key performance indicators (KPI) to be used by all network operators. KPIs should span areas of funding assessment and sustainability, data quality and availability, environmental compliance, operational safety, and adherence to standards and best practices (McArthur et al., 2017).
19. Routinely monitor and assess the design of coastal mooring networks. Routine assessment and coordinated stakeholder planning will promote adaptive management of the network. This review should include a measure of sustainability (continuity of funding) for each coastal mooring in the network (McArthur et al., 2017).

We recommend focused workshops involving coastal moorings operators and institutions to identify and coordinate next steps toward achieving this vision of sustained, robust, integrated networks that meet societal needs. Recommendations for coastal zones from the Implementation of Multi-Disciplinary Sustained Ocean Observations Workshop (Palacz et al., 2017) should also be included as part of these next steps.

AUTHOR CONTRIBUTIONS

KB and CS led the development of the manuscript. All authors contributed to text, figures, and edits.

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[32]https://www.pmel.noaa.gov/co2/story/Open+Ocean+Moorings

[33]http://goa-on.org/

[34]http://odip.org/

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Forecasts of Wave-Induced Coastal Hazards in the United States Pacific Islands: Past, Present, and the Future

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This paper summarizes the existing coastal hazard forecast methods of PacIOOS, such as wave-induced run-up, by focusing on the critical components that need to be addressed in order to improve these forecasts and make them more accurate and available to broader coastal communities. We then propose that a horizontally, two-dimensional numerical modeling approach method should be adopted for developing future wave-induced coastal forecasts. To reach a future in which real-time two-dimensional model-based forecasts are a reality, we identify existing technologies that could lead to improvements, such as: (i) more accurate, accessible and frequently updated bathymetry and topography datasets; (ii) increased computational and software capabilities; and, (iii) more accurate sea level datasets. These advances, combined with crowdsourced-based model-data validation, will result in faster and more accurate forecasting tools that could greatly benefit coastal communities in need of more efficient risk mitigation programs.

Keywords: run-up, coastal hazards, wave forecasts, inundation, high sea level, nearshore bathymetry, crowdsourced validation

INTRODUCTION

Researchers at the University of Hawai'i have successfully developed and implemented real-time forecasts of coastal flooding driven by remotely generated gravity waves impinging on shorelines during periods of high sea level. These forecasts have proven quite valuable to coastal managers and property owners for mitigating threats to lives and property in Hawai'i and in the Republic of the Marshall Islands (RMI; Hess et al., 2015). High sea level events in the future have the potential to increase both in total magnitude and in number of events that exceed present day thresholds. This future scenario compels us to increase our efforts toward accurate and more widespread forecasting of wave-driven run-up and flooding[1]. Research into higher levels of accuracy and coverage for these types of forecasts continues today with projects covering the West Maui, Hawai'i, coastline using new modeling techniques. In the future, we expect that the ability to provide communities with advance notice of wave-driven inundation will be universal for all coastlines. In this manuscript, we provide a brief history of what led to our original forecast and a guide to what we know now. Also, we project into the future and provide recommendations to advance toward universal forecast coverage for all impacted coastlines.

HIGH SEA LEVEL AND WAVE RUN-UP FORECAST DEVELOPMENT

First Phase: Empirical Forecasts

Under the program that is now known as the Pacific Islands Ocean Observing System (PacIOOS), the development of a near-term sea level forecast tool, comprised of a highly accurate tidal re-analysis and non-tidal diurnal and multi-day variability forecast elements, was proposed and initiated. This tool, originally designed for Honolulu Harbor, came online in 2010 and was eventually extended to nine locations in the Hawaiian Islands and in the Insular Pacific (Guiles et al., 2012). This was a valuable first step toward the prediction of inundation for wave-sheltered, low-lying areas in and around these harbors. After developing and validating these 6-day high sea level forecasts[2], the PacIOOS Coastal Hazards Group began to examine how other stakeholder needs could be addressed and how to develop a wave run-up forecast for wave-exposed coastlines based on the empirical model of Stockdon et al. (2006) calibrated with nearshore data collected by PacIOOS co-investigator, Professor Mark Merrifield.

The essential elements were in place to make this forecast a reality. The wave field was provided by NOAA's WAVEWATCH III (WW3; Tolman, 2009) model. Virtual buoys were placed in the model, and 7-day swell forecast directional spectra were acquired on a real-time basis. The WW3 virtual buoys corresponded to PacIOOS' Datawell WaveRider Buoy (Datawell, 2009) locations where near real-time observations are collected. In concert with the wave forecast, the aforementioned 6-day high sea level forecasts provided the localized prediction of the sea level. These two forecasts are the main necessary input components of the empirical wave run-up model.

Initially, two locations were chosen to create the wave run-up forecast—Waikīkī on the South Shore of O'ahu, and Rockpiles on the North Shore of O'ahu. The locations were selected based on the available near-shore pressure records collected by Merrifield. These records were unique in that they spanned periods of time when either the PacIOOS Barbers Point WaveRider Buoy was in place to provide data for Waikīkī or when the PacIOOS Waimea Buoy was in place for the pressure gauges deployed at Rockpiles. These data allowed for the adjustment of the parameters in the Stockdon model to accommodate the unique conditions at each location.

From the above description, it is clear that the success of the parameterized model forecast products depended on multiple factors that were not available a decade before. A short list includes: accurate wave model (WW3), accepted parameterized model (Stockdon et al., 2006), real-time wave observations (PacIOOS Wave Buoy Program), accurate sea level forecast (PacIOOS 6-Day High Sea Level Forecasts), and including (though not directly limited by) field observations for specific site implementation. Since 2012, this forecast has been available to the public and is continually undergoing threshold verification and documentation.

During implementation of the O'ahu wave run-up forecasts, a severe wave run-up event in the RMI led to a government-declared state of emergency, and stakeholders asked PacIOOS if they could help by providing advanced notification to the community before similar future events (Iwamoto et al., 2016). Fortunately, the data analysis for two other locations became available in the RMI: Roi-Namur (Kwajalein Atoll) and Majuro Atoll. Additional parameterization work done by Merrifield et al. (2014) and Becker et al. (2014) modified Stockdon's empirical model by extending it to account for run-up on a fringing reef system. Two forecasts were constructed and made publicly available online by 2014 with threshold verification and historical event analysis. Each of the forecasts, one for Kwajalein Atoll and one for Majuro Atoll, incorporated directional filters for the prevailing wave forecast, thus allowing for shoreline-specific forecasts. This represented a step toward extending the parameterization model from being statistically valid at a single location to being valid along a range of geographic locations[3]. Other institutions have followed the same empirical approach, including the United States Geological Survey *Total Water Level and Coastal Change Forecast Viewer*, and the Coastal Data Information Program at Scripps Institute of Oceanography *Potential Flooding Index* products. These efforts now extend the empirical wave run-up forecast coverage to coastal regions along the eastern and western United States seaboard.

One critical part of the forecast development, for both the high sea level and wave run-up forecasts, is to establish accurate and useful metrics for extreme conditions. Part of this can be accomplished through historical data analysis and hindcasting, but this may not always yield thresholds that relate to the forecast user base. Effective thresholds require local knowledge, images, descriptions—all forms of communication that make the forecast output contextually relevant for the user. During development, PacIOOS researchers began asking partners, agencies, interested parties, and friends to record impactful situations. This step takes time to generate a robust collection of events and their

[1] A note on terminology. Run-up is considered the maximum topographic elevation the water reaches on land, and in the case of swell wave-driven run-up (as opposed to tsunami run-up, for instance) it is usually quantified as the elevation reached by 2% of wave bores running up the shore (the 2% exceedance point). The inundation is the distance the seawater travels inland (measured horizontally) that is driven by wave run-up or non-swell wave processes affecting the sea level height at the shore. Flooding results from significant and/or repeated inundation. Inundation often occurs somewhere within a region where high run-up occurs, but this all depends on the near-coast topography.

[2] http://www.pacioos.hawaii.edu/shoreline-category/highsea/

[3] http://www.pacioos.hawaii.edu/shoreline-category/runup/

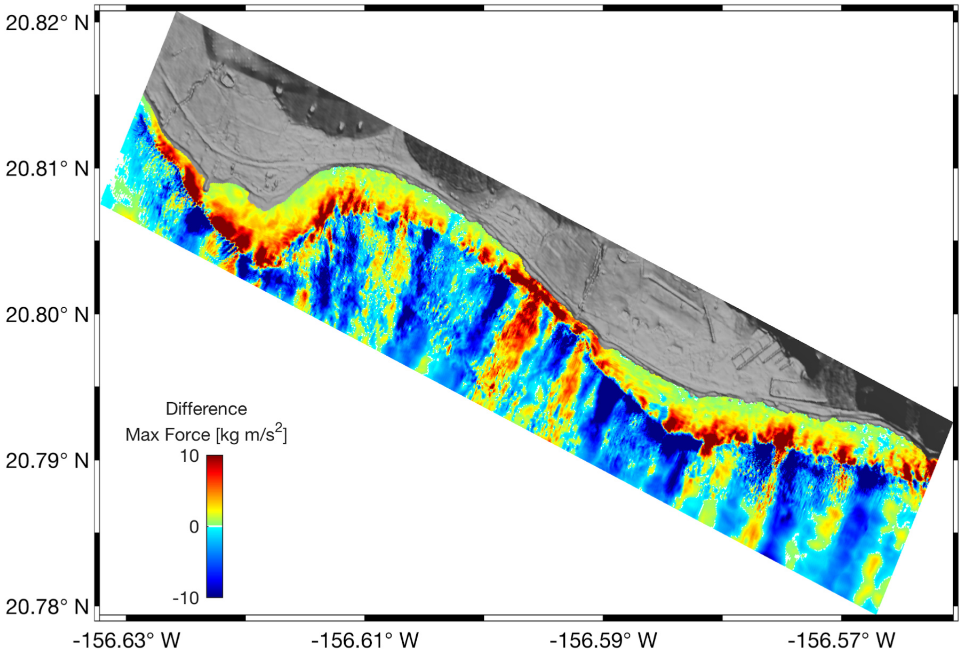

FIGURE 1 | The difference in maximum hydrodynamic force per unit shoreline width from the BOSZ model for a wave event at Olowalu, Ukumehame, West Maui (high tide minus low tide). The tidal levels where set at MSL + 0.6 m for high tide and MSL – 0.3 m for low tide. The wave input conditions are identical in both scenarios, arriving from due south with H_s = 1.5 m, T_p = 14 s, and a typical directional spreading of 30°.

impacts. However, without this type of documented validation, the forecasts would have limited value at most locations.

Around the time that the Kwajalein and Majuro forecast tools were released, we began exploring ways to accurately extend the forecasts along a coastline without being confined (in terms of statistical reliability) to one narrow beach zone. This exposed one of the weaknesses of using the empirical model: for every location that a forecast was desired, a fairly extensive field program was needed. As the nearshore wave models were becoming more mature and the available computational power continued to increase, the idea of applying modern numerical models to address this problem began to evolve.

Recent Advancements in Forecast Development

Over the past two decades, numerous numerical models for water wave propagation and transformation have been developed. Phase-averaged models like WAVEWATCH III and SWAN (SWAN Team, 2015), which propagate wave energy over long distances with computational efficiency, are robust solutions that have been integrated into the general environmental prediction regime. These schemes work with averaged/integrated quantities, they do not properly account for infragravity[4] (IG) waves or run-up. To accurately resolve IG waves we need to use phase-resolving models. A number of these models have been developed, including COULWAVE (Lynett et al., 2002), FUNWAVE (Shi et al., 2012), XBeach (Roelvink et al., 2009), and BOSZ (Boussinesq Ocean and Surf Zone model; Roeber and Cheung, 2012). The latter was chosen for the development and implementation of our forecast. These phase-resolving models not only allow for the generation and propagations of IG waves, they explicitly track the free surface along the wet-dry boundaries which can then be used to directly compute the run-up along a coastline.

Figure 1 provides an example of the level of detail and kind of information that can be obtained from such models. Forcing BOSZ with a southerly wave event with significant wave height H_s = 1.5 m and peak period T_p = 14 s, **Figure 1** shows the difference in hydrodynamic force (kg m/s$^{2)}$ per unit shoreline between high tide (MSL + 0.6 m) and low tide (MSL − 0.3 m) at Olowalu, Ukumehame, West Maui. Under high tide conditions, the reef becomes less effective in dissipating swell energy through breaking compared to a low tide level. The hydrodynamic force increases at high tide levels, i.e., the resulting waves over the reef lagoon and along the shoreline are not only higher but also faster. Though these results are site-specific, locations with fringing reefs tend to face an increased risk of damaging and erosive wave conditions at high sea levels.

Although the existing empirical wave run-up models can provide very useful real-time results, they are based on highly simplified assumptions (such as one dimensionality), and are not valid everywhere. On the other hand, a horizontally two-dimensional (2-D) model provides a more complete picture of the gravity and IG wave dynamics. Running a phase-resolving

[4]Commonly, the term "infragravity waves" refers to gravity waves at periods from approximately 25 s to a few minutes. Here we include waves in this term that have periods as long as an hour.

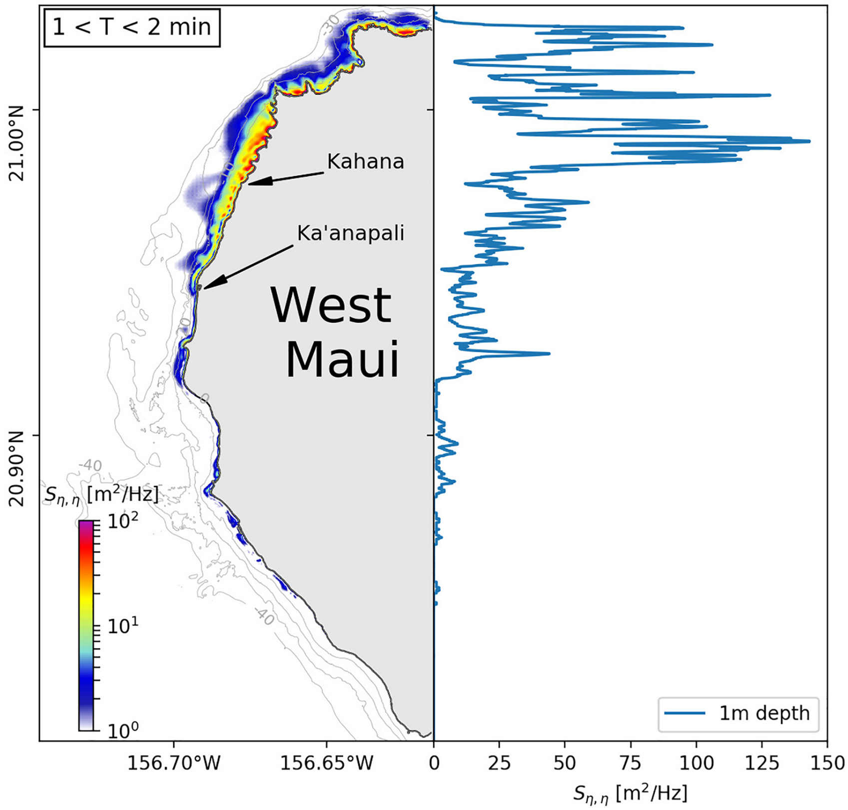

FIGURE 2 | Left panel: Map of computed power spectral density (PSD) along the West Maui coastline from the BOSZ model, in the 1–2 min IG band. Right panel: The corresponding PSD levels along the 1 m depth contour line. The sea/swell input conditions are from due north with H_s = 2 m and T_p = 16 s.

model in 2-D mode requires the following inputs: (i) bathymetry and topography; (ii) directional spectra that are representative of the sea/swell conditions in the vicinity of the wavemaker; and (iii) water/tide level information. Since the accuracy of a 2-D model-based wave run-up forecast greatly depends on these inputs, it is crucial to assure that they are as accurate as possible.

In addition to swell waves, infragravity (IG) waves play an important role in the total run-up. Similar to the response of the coastline to tsunamis, an IG wave field can trigger resonances in harbors, bays, and over other bathymetric features. As a result, large computational domains are necessary to capture these large-scale responses and the subsequent variations of wave run-up, especially along fringing reefs and near headlands. **Figure 2** provides an example of such spatial variability of the power spectral density (PSD) in the 1–2 min period band, found in the BOSZ model in response to sea/swell forcing from due north with significant wave height H_s = 2 m and peak period T_p = 16 s.

For the West Maui domain, under a National Oceanographic and Atmospheric Administration (NOAA) Coastal Resilience award, we have brought together all the necessary pieces to implement a real time 2-D inundation forecast. WWIII is feeding a high resolution SWAN model that provides 42 directional wave spectral at the exterior of two large BOSZ model grids. The BOSZ model was selected for familiarity after testing three separate models (publication in works). Sea level comes from a new high resolution sea level forecast for Lahaina in the center of the domain. The forecast requires one dedicated server of 40 cores for the BOSZ model and will provide 6 days of run-up forecast for thirteen zones along the shoreline.

EXPECTATIONS AND RECOMMENDATIONS FOR PROJECTED FORECAST DEVELOPMENT

To actualize a future where any impacted coastal location on the globe has a live, near-term wave run-up forecast that provides the accuracy equivalent to or better than existing forecasts will require significant but achievable progress. We have identified a set of technologies that will be necessary to meet this goal. These include data acquisition, computational efficiency, and impact validation.

There are two main types of data required for the live model approach to forecasting. One is the need for accurate real-time sea level at periods longer than about an hour. This data is required for the empirical model as well as for any other accurate wave run-up forecast. The sensitivity of run-up to sea level conditions precludes using just global tide solutions and/or remote sensing (at its current level of accuracy) if high forecast accuracy is desired. In the future, it is likely that the combination of eddy resolving Global Circulation Models (GCM), advances in remote sensing, and a proliferation of sea level gauges, will lead to accurate coastal sea level prediction being available for most coastal areas.

The other data that is required for the live 2-D model approach is accurate nearshore bathymetry and topography. This has a complication in that the nearshore topography (and in some cases the bathymetry as well) is often changing within very short time scales due to natural and anthropogenic causes. New technologies are being introduced that will allow for the collection of these datasets for coastlines with high population density (Casella et al., 2016). Products such as Google Earth continuously advance in the assimilation of data. Also, existing digital elevation model services such as Autodesk ReCap and DroneDeploy for the construction and agriculture sectors, are now appealing to the general public. One could imagine in the near future that citizen scientist networks, subscribers to crowdsourcing data collection apps, or another conduit yet to be created will be able to respond to simple requests in areas where new topography is necessary. Such requests might be filled by the general public flying their consumer drones and submitting the images for photogrammetric processing.

Apart from community sourced topography, new bathymetric lidar is now available for drone usage (e.g., RIEGL Bathycopter, Fugro RAMMS, etc.), so the cost and complexity of small scale nearshore bathymetric surveys will drop exponentially. Additionally, with the smaller scale and lower heights of acquisition, the bathymetric accuracy will increase. In tandem with the new drone technology is the implementation of small scale side scan sonar mounted on autonomous surface vehicles (e.g., EvoLogics Sonobot, Seafloor Systems Echoboat, implementation example see Giordano et al., 2016). These new advances mean that the critical bathymetric and topographic component for implementing live model-based forecasts will cease to be a major impediment. Additionally, changes in model accuracy due to fluctuation in the nearshore topography will adjust as updated topographic models are generated in a timely response cycle as opposed to waiting multiple years.

To increase the accuracy of the live model-based forecast approach one can reduce the grid size and increase the resolution of the input wave spectrum. Both of these conditions will happen in time naturally as increased processing power becomes more accessible. But advances in the numerical schemes of the Boussinesq phase-resolving models used will continue as well. The potential to optimize some of the computational workload and shift it toward Graphics Processing Unit (GPU) style massive multithreading remains (Kim et al., 2018). This should eventually lead to much higher accuracy and much shorter run times, as it has for other types of computational fluid dynamic models.

The next critical advancement in bringing live 2-D numerical model forecasts of wave run-up to many (if not all) coastal zones in the future is the process of validation. Validating the forecasts often requires many man hours of on-site assessments, plus photo and video records for each individual event. This critical information was necessary to make our original empirical forecasts useful and accurate, and it is equally necessary for the live numerical models. New community-based methods of collecting this information are being implemented now which should increase the amount of observations while decreasing the workload on professionals.

These community-based ground-truthing methods, as they mature, will bring a whole new level of value to run-up and inundation forecast products. The Hawai‘i and Pacific Islands King Tides Project, a citizen scientist crowdsourced initiative led by the University of Hawai‘i Sea Grant College Program, has already collected thousands of images revealing the extent of specific inundation events and how they impact local coastlines. A similar approach will be employed to document the impacts of wave run-up along West Maui. Efforts like this are spreading quickly (e.g., Massachusetts Institute of Technology's product Riskmap.org), and our expectation is that crowdsourced data collection methodologies will aggregate and be standardized over time. Federal agencies, such as Federal Emergency Management Agency's *Disaster Reporter* and associated mobile app, also take advantage of community-based data and information collection.

As the crowdsourced methods become widespread and mature in the level of accuracy and coverage, the other forecast technologies will advance in conjunction. The future of the wave run-up and inundation forecasts will become an interesting interplay between scientists, hazard management agencies, and end users. We have realized the importance of communicating the forecast products in a way that enables the user to mitigate risk most effectively. An additional realization is that we, the forecast creators, will be relying on the end users directly for critical components necessary to increase accuracy and coverage. This adaptive confirmation and application of the forecast models will strengthen their usage and avoid major pitfalls of similar efforts (Oreskes et al., 1994).

We are optimistic that in the near future there will be a distinct increase in both the area of coastline covered by run-up and inundation forecast tools and an increase in the accuracy of those tools. In other words, the deployment of live 2-D wave models in the nearshore combined with a campaign of event validation will lead to much higher levels of risk mitigation and response. These advancements will result in more users that rely on these forecasts. A threshold of acceptability is dawning for this type of forecast, and once the tools mature and become widespread, their ubiquitous inclusion into existing public forecasts such as those of the NOAA's National Weather Service should be encouraged. Institutionalization of these forecasts increases stakeholder reach, thereby increasing societal benefit.

With the goal of bringing inundation forecasting to the level of existing national public forecasts, we recommend forming a national steering committee to begin planning the extensive process to make this a reality. A set of workshops in the near future could help bridge the inundation community together and illuminate an acceptable objective that matches the accuracy and availability of public forecasts like precipitation, winds, tides, etc. The committee could outline and bring together the cross-discipline science needed for crowd sourced validations and citizen scientist data collection. Also, a national steering committee would help promote the funding necessary to make the forecasts tools a reality in a timely fashion.

AUTHOR CONTRIBUTIONS

MG led the review, the design, and the development of the manuscript. AA and VR generated the figures and associated text. MI, FL, and DL contributed to the focus of the text and to the drafting of the manuscript. All authors have reviewed the final version of the manuscript and approved it for publication.

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Observing Sea States

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Sea state information is needed for many applications, ranging from safety at sea and on the coast, for which real time data are essential, to planning and design needs for infrastructure that require long time series. The definition of the wave climate and its possible evolution requires high resolution data, and knowledge on possible drift in the observing system. Sea state is also an important climate variable that enters in air-sea fluxes parameterizations. Finally, sea state patterns can reveal the intensity of storms and associated climate patterns at large scales, and the intensity of currents at small scales. A synthesis of user requirements leads to requests for spatial resolution at kilometer scales, and estimations of trends of a few centimeters per decade. Such requirements cannot be met by observations alone in the foreseeable future, and numerical wave models can be combined with *in situ* and remote sensing data to achieve the required resolution. As today's models are far from perfect, observations are critical in providing forcing data, namely winds, currents and ice, and validation data, in particular for frequency and direction information, and extreme wave heights. *In situ* and satellite observations are particularly critical for the correction and calibration of significant wave heights to ensure the stability of model time series. A number of developments are underway for extending the capabilities of satellites and *in situ* observing systems. These include the generalization of directional measurements, an easier exchange of moored buoy data, the measurement of waves on drifting buoys, the evolution of satellite altimeter technology, and the measurement of directional wave spectra from satellite radar instruments. For each of these observing systems, the stability of the data is a very important issue. The combination of the different data sources, including numerical models, can help better fulfill the needs of users.

Keywords: sea state, waves, altimeter, SAR, swell, remote sensing, buoy, microseisms

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1. INTRODUCTION

The development of modern measurements and prediction of sea states has been strongly linked to naval and shipping activities. Here we will define "sea state" rather narrowly as surface gravity waves with periods shorter than 5 min, but this "sea state" is obviously studied in a wider context of all the sea conditions that affect navigation, including winds, currents, and sea ice. We cannot ignore winds and currents that, together with sea ice, are the forcing agents that define the properties of waves, with some possible feedback of waves on these other phenomena. This is discussed by Villas Bôas et al. (2019). Here we only focus on surface gravity waves, which are of interest for a very broad range of applications.

Sea states have been observed for a few centuries, either as the main reason for the measurement, as in ship logs (Gulev et al., 2003), or as a by-product of other observations. Indeed, ocean waves have an obvious signature in many other measurements ranging from seismic observations (Bertelli, 1872) to ocean remote sensing, such as sea level monitoring from satellite altimeters (Minster et al., 1991), or radiometric measurements of winds and salinity (e.g., Reul and Chapron, 2003).

All of these measurements, either made on purpose or arising from other applications, have important uses for human activities at sea and on the coast. In particular, waves affect shipping and harbor operations, with data provided by meteorological services under the Safety of Life at Sea (SOLAS) convention, which is why many wave buoys around the world are managed by port authorities or located near important harbors, while naval architecture still relies primarily on visual observations (Bitner-Gregersen et al., 1995; IACS, 2001). Other applications have developed very localized measurement systems, in particular for coastal hazards and beach morphodynamics (e.g., Holman and Stanley, 2007). Except for the recent launch of CFOSAT (Hauser et al., 2017), measuring ocean waves has not been the primary goal for satellite missions. Still, these data are very useful but the observing system has not been optimized to sample storms in space and time. Wave observations are particularly useful for the investigation of air-sea fluxes of momentum and heat (Cronin et al., 2019), gas, aerosols (Veron, 2015) and parameterizations in weather predictions or climate models. Similarly, the ever-growing network of seismic stations on land (Romanowicz et al., 1984; Tytell et al., 2016) are providing opportunities for long-term sea state monitoring, even in remote locations (e.g., Bromirski et al., 1999; Ardhuin et al., 2012; Retailleau et al., 2017), or, at the very least, some independent data for validating trends of other observing systems.

All existing observations, as well as emerging new technologies, are complementary. Starting from the analysis of requirements from user communities in section 2, we review today's wave observations in section 3, and, in section 4, look forward to the next decade on how these could be better organized and exploited to map the space and time variability of sea states. Recommendations follow in section 5.

2. REQUIREMENTS FOR SEA STATE MEASUREMENTS AND CONNECTION WITH OTHER ESSENTIAL CLIMATE VARIABLES

Although this paper is focused on wind-generated waves, the importance of the forcing factors that are the wind, currents and sea ice cannot be ignored, and they are very important when interpreting observations or validating numerical models.

2.1. General Definitions

Here we consider that statistical properties of the surface elevation are fully described by the wavenumber-direction wave spectrum $F(k,\theta)$, which describes how the surface elevation variance is distributed across wavenumbers k and directions θ, with θ the direction from[1] which the waves are propagating, hence opposite to the direction of the wavenumber vector $\mathbf{k}$. Possible correction for non-linear effects are given by Fedele and Tayfun (2007) and Janssen (2009), with one particular application demonstrated by Leckler et al. (2015). This approach is most appropriate for waves in deep water. It is customary to transform wavenumbers to frequencies using the linear dispersion relation

$$\sigma^2 = g\mathbf{k} \tanh(\mathbf{k} D) \quad (1)$$

where g is acceleration due to gravity, D is the water depth, and σ is the relative radian frequency. Currents are accounted for using

$$\omega = \sigma + \mathbf{k} \cdot \mathbf{U}_A(\mathbf{k}) \quad (2)$$

where $\omega = 2\pi f$ is the absolute radian frequency, as measured in a frame of reference attached with the solid Earth, and $\mathbf{U}_A$ is the phase advection velocity that is generally a function of the wavenumber vector $\mathbf{k}$ (Stewart and Joy, 1974; Andrews and McIntyre, 1978). The radian frequency $\sigma = 2\pi f_r$ is the relative frequency that would be measured in a reference frame moving with the velocity $\mathbf{U}_A$.

This dispersion relation gives a frequency-direction wave spectrum, with an example shown in **Figure 1**

$$E(f,\theta) = \frac{\partial k}{\partial f} F(k,\theta). \quad (3)$$

The difference between f and f_r is particularly important in the presence of currents faster than 0.2 m/s. For completeness, we briefly recall the definitions of common sea state parameters (IAHR Working Group on Wave Generation and Analysis, 1989).

The significant wave height H_s is defined as 4 times the standard deviation of the surface elevation,

$$H_s = 4\sqrt{\int E(f)\mathrm{d}f}, \quad (4)$$

with other usual notations SWH and H_{m0}. The surface heave spectrum is

$$E(f) = \int_0^{2\pi} E(f,\theta)\mathrm{d}\theta. \quad (5)$$

For each frequency, another four parameters are readily measured from the spectra and co-spectra of three co-located time series of wave-associated variables such as the heave, pitch

[1]This particular convention, with direction *from* is commonly used in coastal applications. Some other applications prefer to use the direction *to*.

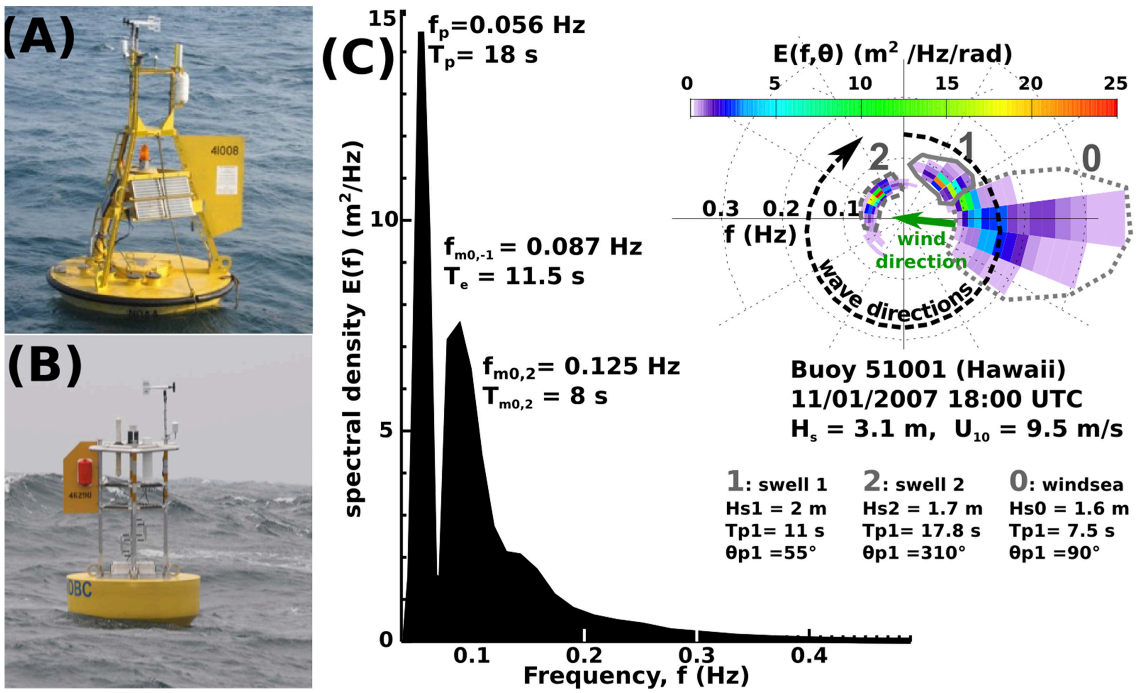

FIGURE 1 | (A,B) show typical layout of NBDC wave buoys with old and new designs. Wave measurements are made by a motion package in the hull and wind measurements use an anemometer at 5-m height. **(C)** Example of wave information derived from a buoy, ranging form the common estimate of H_S to the heave spectrum $E(f)$ in black, or a two-dimensional directional spectrum $E(f,\theta)$ in colors. Note that the buoy does not measure the directional spectrum but, for each frequency, only the "First 5" parameters from which the directional spectrum is estimated here using the Maximum Entropy Method (Lygre and Krogstad, 1986). For many applications it is customary to partition the spectrum into a windsea region (dotted contour labeled 0), and swells (solid and dashed contours labeled 1 and 2) which are usually ordered by decreasing wave energy. For each partition, height, period and direction parameters are estimated in the same manner as they would be estimated from a full (frequency-direction) spectrum.

and roll of a surface-following buoy (Cartwright and Longuet-Higgins, 1956), or its 3-component acceleration vector, or the combination of pressure and horizontal velocity. These are

$$a_1(f) = \int_0^{2\pi} E\left(f,\theta\right)\cos\theta \,\mathrm{d}\theta, \quad (6)$$

$$b_1(f) = \int_0^{2\pi} E\left(f,\theta\right)\sin\theta \,\mathrm{d}\theta, \quad (7)$$

$$a_2(f) = \int_0^{2\pi} E\left(f,\theta\right)\cos(2\theta) \,\mathrm{d}\theta, \quad (8)$$

$$b_2(f) = \int_0^{2\pi} E\left(f,\theta\right)\sin(2\theta) \,\mathrm{d}\theta. \quad (9)$$

The combination of $E(f)$, $a_1(f)$, $b_1(f)$, $a_2(f)$, $b_2(f)$, or any other equivalent parameters (Kuik et al., 1988), forms the set of "First 5" spectral wave parameters.

One year of hourly wave directional wave measurements contains roughly 8,760 records, and a "First-5" dataset with 50 frequencies would have 250 data points for each record. These 2.2×10^6 data values per year provide a much better description of the sea state than a much reduced set of a few integrated parameters that is necessary for many applications.

For the purpose of providing weather information or for comparing different sensors, it is useful to use a reduced set of values. For this spectral partitioning methods are very useful in associating energy to a common peak, which is a great way to analyze swell data (Gerling, 1992; Hanson and Phillips, 2001; Portilla et al., 2009). This is illustrated with the gray contours on **Figure 1C**.

Mean wave periods are generally estimated from moments of the wave spectrum as follows for the p^{th} moment period,

$$T_{m0,p} = \left[\left(\int_0^{f_{\max}} f^p E(f,\theta)\mathrm{d}f\right) / \left(\int_0^{f_{\max}} E(f)\mathrm{d}f\right)\right]^{-1/p}. \quad (10)$$

These periods, in particular $T_{m0,2}$ defined by Equation (10) with $p = 2$, are sensitive to the practical choice of the maximum frequency $f_{\max}$. They are also markedly different in the presence of currents when measured with a drifting instrument or with a moored instrument.

We have emphasized currents in these definitions of sea state parameters because of the evidence of the role currents in wave time series (e.g., Ardhuin et al., 2012; Gemmrich and Garrett, 2012). Recent research has further revealed that away from the coast (Magne et al., 2007), even outside the well known boundary currents, ocean currents are the main source of wave height variability at scales under 200 km, as illustrated in **Figure 2**

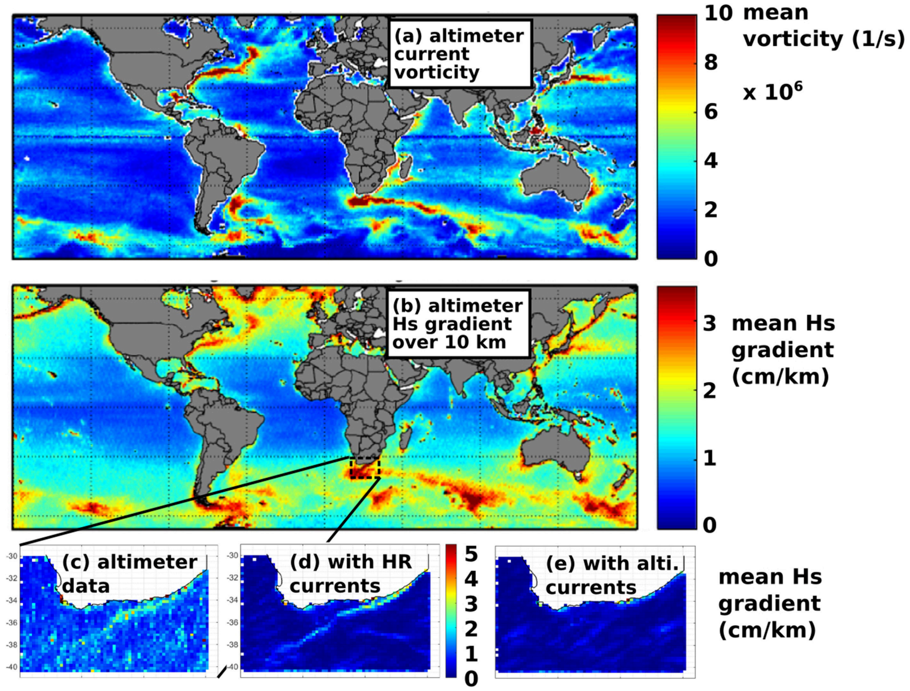

FIGURE 2 | (a,b) show 4-year mean (2013-2016) computed using the constellation of 4 satellite altimeters, of current vorticity estimated from gridded altimeter data, and along-track gradient of significant wave height. **(c)** is a higher resolution grid over the Agulhas current for August 2015, compared to **(d)** a WAVEWATCH III model run forced by 1-km resolution modeled currents, and **(e)** forced by altimeter-derived gridded currents (Adapted from Quilfen et al., 2018 as authorized by Elsevier).

(see also Gallet and Young, 2014; Ardhuin et al., 2017a; Quilfen et al., 2018).

2.2. Updating Requirements for Sea State Measurements

Sea states are thus much less uniform than previously imagined, with important consequences for applications. Also, the importance of waves for coastal sea level (Ponte, 2019) , is naturally providing requirements for the accuracy and stability of wave heights and periods that are key variables for explaining extreme sea level (e.g., Stockdon et al., 2006; Poate et al., 2016; Dodet et al., 2018). In particular, consistency with the requirements on mean sea level, is calling for an adjustment on the requirements for sea state as previously defined by GCOS-200 (Belward, 2016). Given that the maximum run-up is of the order of the offshore significant wave height, we may specify separate requirements for the sea state parameters at large (global to regional) scales, and stricter requirements for coastal sea state parameters, which should apply right outside of the surf zone, as proposed in **Table 1**.

Accuracy levels of directional wave measurements required by various user groups vary as already identified at OceanObs'09 (Swail et al., 2009). However if the most stringent requirement is followed then the needs of the diverse user groups and applications will be met. This requires centimeters for wave heights, tenths of seconds for wave periods, and 2–5° for directions.

The WMO (World Meteorological Organization) lists the wave requirements in detail for various applications (WMO, 2017a,b). Typically, these requirements specify significant wave height accuracy of 5–10% (or 10–25 cm); wave periods of 0.1–1 s, wave directions to 10°, and wave spectral densities to 10 percent. For certain applications, especially in coastal regions, required accuracies are higher, which presents significant challenges.

Enforcing these requirements for any directional wave measurement system, a genuine ground-truth would be established.

Quantification of multi-component wave systems with differing directions at the same frequency can affect various wave related applications, this is particulary the case for waves in opposing directions in the case of microseism sources (Hasselmann, 1963; Obrebski et al., 2012). Therefore, the accuracy and resolution of the wave directions are critical.

Buoy technology is available that can provide good quality measurements for the 'First 5' parameters (Equations 5–9). The generalization of such technology and the monitoring of the data quality is further discussed below.

New and future satellites such as CFOSAT (Hauser et al., 2017) and SKIM (Ardhuin et al., 2018) should be able to go beyond these "First 5," with unprecedented directional resolution, but their temporal sampling cannot make them the backbone of a sea state monitoring system. Still, such new data can provide a transformation of our understanding and advance our numerical modeling capabilities.

TABLE 1 | Requirements on sea state measurements according to GCOS-200, and propositions for updates. The requirements on stability should be understood as applicable to all percentiles of the heights or period distributions.

	Variable	Frequency	Resolution	Uncertainty	Stability
GCOS-200	H_s	3-hourly	25 km	10 cm	5 cm/decade
GCOS-200	regional sea level	hourly	10 km	1 cm	$<$ 1 mm/year
WMO	H_s	??	??	5-10% or 10 to 25 cm	??
WMO (2017)	$T_{m0,2}$	??	??	0.1 to 1 s	??
WMO (2017)	θ_m	??	??	10 deg	??
this paper	global to regional H_s	3-hourly	25 km	10 cm or 5%	5 cm/decade
this paper	coastal H_s	1-hourly	1 km	10 cm or 5%	$<$ 1 mm/year
this paper	regional $T_{m0,-1}$	3-hourly	25 km	0.2 s	$<$ 0.1 s/decade
this paper	regional $T_{m0,2}$	3-hourly	25 km	0.2 s	$<$ 0.1 s/decade

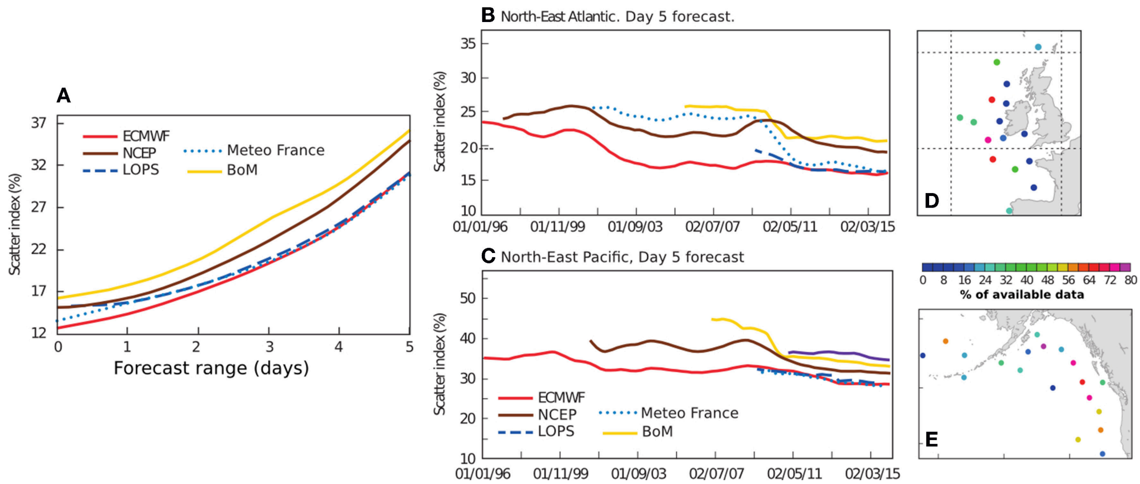

FIGURE 3 | (A) Scatter index for H_s from 5 numerical wave forecasting systems against a selection of mostly Northern Hemisphere wave buoys, as a function of forecast range, for the months of September 2015 to August 2016. These forecasts are produced by ECMWF (Reading, UK, with reanalysis available as ERA5), NOAA/NCEP (MD, USA), Meteo-France (Toulouse, France, now available as part of the Copernicus Marine Environment Monitoring Service, marine.copernicus.eu), the Bureau of Meteorology (Melbourne, Australia) and LOPS (Brest, France, available in hindcast at ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST/). Focusing on the 5-day forcasts, **(B,C)** show the evolution of the model error with the years, at selected buoys in the North-East Atlantic and the North-East Pacific, with locations shown in **(D,E)**. Adapted from Bidlot (2016) as authorized by ECMWF.

This was demonstrated in the last decade with swell monitoring from SARs (Ardhuin et al., 2009) leading to the development of new parameterizations for wave dissipation by Ardhuin et al. (2010) leading to a typical 30% error reduction in H_s estimates (see **Figure 3** and Roland and Ardhuin, 2014). These parameterizations are now used at most wave forecasting centers: these include Meteo-France since 2010, NCEP since 2012, the Bureau of Meterology since 2010, and ECMWF in June 2019 with the cycle 46r1 of their Integrated Forecasting System, after demonstration at LOPS since 2008. Unfortunately the ECMWF ERA5 reanalysis uses an older version Cycle 41r2 (Hersbach and Dee, 2016).

Satellite data are also used at Meteo-France and ECMWF for correcting the initial conditions of wave models, and in the production of reanalyses. Whatever their use, whether for improving model parameterizations or for assimilation in forecasting and reanalyses, satellite data ultimately relies on the calibration and validation using *in situ* buoys (e.g., Stopa et al., 2016).

2.3. Trends and Interannual Variability

A specific aspect of observation requirements is the stability of the estimates of sea state parameters. The wide range of estimates of trends in wave heights, from Young et al. (2011) to Hemer et al. (2013) is certainly calling for modesty when defining requirements on the stability of sea state estimates. Understanding past trends is necessary if one wishes to extrapolate them in the future, here are two examples.

In the Southern Ocean, there is growing evidence from both *in situ* measurements and model studies that westerly winds intensified from 1987 to 2011 (Hande et al., 2012), partly associated with a general expansion of the tropics caused by global warming (Lucas et al., 2014), and partly due to an increase in extension of the sea ice which persisted up to 2014 (Turner and Comiso, 2017).

In the tropical Pacific, the contribution of inter-annual variability patterns is particularly strong, these include the El Nino Southern Oscillation and the longer Interdecadal Pacific Oscillation, IPO (Fyfe et al., 2014). In particular, trade winds over the west Pacific have increased from 1992 to 2011 associated with a particular phase of the IPO (England et al., 2014; Fyfe et al., 2014). Both of these increases have been reflected in altimeter derived trends across the global ocean (Young et al., 2011), and there is no known physical process that could lead to a long-term sustained trend of that 0.5–2% per year. Other evidence suggests inter-annual variability of H_s is relatively small, typically under 8%, as quantified by wave hindcasts over several decades (Stopa et al., 2013).

Young et al. (2011) estimated H_s trends from 1985 to 2008 using the dataset of Zieger et al. (2009) who calibrated each altimeter mission with respect to moored buoys and by cross-calibrating the different satellite platforms. The H_s calibration with buoy observations was based on nearly 8,000 co-locations. The calibration was performed for H_s <8 m; therefore wave heights above 8 m remain largely unconstrained by direct buoy observations. In tropical storms where H_s are large, there are often heavy rains which might introduce errors (Guymer et al., 1995; Young et al., 2017).

The trends for the 99th percentile (P99) of H_s presented in Young et al. (2011) and adapted here in **Figure 4** are much larger (1–5 cm year^{-1}) than the GCOS-200 requirements (**Table 1**). However, the global trend in average wave height is small with possibly only the Southern Ocean showing statistically significant positive trends (Young et al., 2011). There is a reasonable level of confidence in mean trends determined from satellite data; however, accurately determining trends in upper percentiles is more challenging. Although a comprehensive validation of altimeter performance under such extremes conditions is still lacking, the limited comparisons with buoy data and extrapolations to extreme value conditions indicate that reasonable data can be obtained (Young et al., 2017; Takbash et al., 2019). In addition, however, there needs to be a sufficiently large number of satellite passes to form stable values of the upper percentiles. This is a demanding requirement, as altimeters, with their large spatial separation between ground tracks, tend to under-sample small-scale storms, such as tropical cyclones (Takbash et al., 2019). As a result, questions have been raised about whether stable values of these upper percentiles can be measured and whether the increase in the number of satellites in orbit may introduce a spurious positive trend in long term altimeter estimates. As both the length of the altimeter dataset and the number of satellites in orbit increases our ability to answer these question will improve.

Trends for H_s from buoys have been estimated from time series spanning several decades off the West coast of the United States and Canada. These generally show increasing wave heights (Allan and Komar, 2000; Gower, 2002; Menéndez et al., 2008; Ruggiero et al., 2010). However, these trend estimates are strongly distorted by changes in buoy hull, sensor payload, sampling acquisition, and processing (Gemmrich et al., 2011), which we further discuss in section 3.1.

Many wave climate studies conducted using model hindcasts forced by multi-decadal reanalysis datasets (wind fields and ice concentrations) have been conducted (e.g., Wang and Swail, 2001; Caires and Sterl, 2005; Hemer et al., 2009; Fan et al., 2012; Reguero et al., 2012; Stopa et al., 2013). None of these studies correct for the changing quality of the reanalysis wind field that introduces temporal changes as discussed in several studies that use the Climate Forecast System Reanalysis (Chawla et al., 2013; Rascle and Ardhuin, 2013; Stopa and Cheung, 2014). Monthly H_s residuals in **Figure 5** with respect to merged satellite radar altimetry dataset reveals spatial as well as temporal changes in the time series. It is clear that the H_s residuals are larger for larger sea states (e.g., H_s P95). The strong change in H_s residuals, namely in the Southern Hemisphere, in 1994 was linked to the inclusion of the SSM/I satellite radiometer into the reanalysis data (Rascle and Ardhuin, 2013). Since the quantity as well as quality of the satellite observations being assimilated into reanalysis datasets changes in time (Saha et al., 2010; Dee et al., 2011), wave hindcasts driven by reanalysis are strongly related to the changes in wind forcing. Therefore, hindcasts in the current status cannot meet the GCOS-200 H_s requirements of 5 cm/decade since **Figure 5** shows the H_s residuals are at least 10 cm/decade for the median and 50 cm for the 95th percentile. Certainly, the reference dataset used in this figure, satellite altimeters, also has time and space stability errors.

The urgency of understanding total sea level at the coast (e.g., Melet et al., 2018) is clearly calling for a stability that matches that of the offshore sea level. This is particularly important in today's transition where the total ice-shelf melt contribution to sea level rise is still limited to a few centimeters. In the long term, with sea level rise of several meters, the few centimeters to decimeters due to waves will probably be less important, except where changes are dramatic, as is the case in the Arctic (e.g., Stopa et al., 2016) and possibly in tropical cyclones (Shimura et al., 2016).

Finally, extreme waves and their trace in the geological record are used as evidence for past storminess using paleo-shorelines (Bouchette et al., 2010), ripple marks (Allen and Hoffman, 2005) or wave-transported boulders (Cox et al., 2016). It is thus very important to link extreme sea states to these geological marks under present climate conditions from shoreline features (Ashton et al., 2001) to ripples (e.g., Ardhuin et al., 2002), and boulders (Autret et al., 2016; Kennedy et al., 2016), in order to better understand the geological record and past climates.

3. EXISTING MEASUREMENT TECHNOLOGIES AND THEIR LIMITATIONS

3.1. *In-situ* Measurements

The majority of existing *in-situ* wave measurements are made from moored buoys in the coastal margins of North America and Western Europe. There are large data gaps in the rest of the global ocean, particularly in the Southern Ocean and the tropics while other existing observational systems often have considerable coverage in these areas, such as the Argo temperature/salinity profiling floats. Also, sea state measurements are often missing at

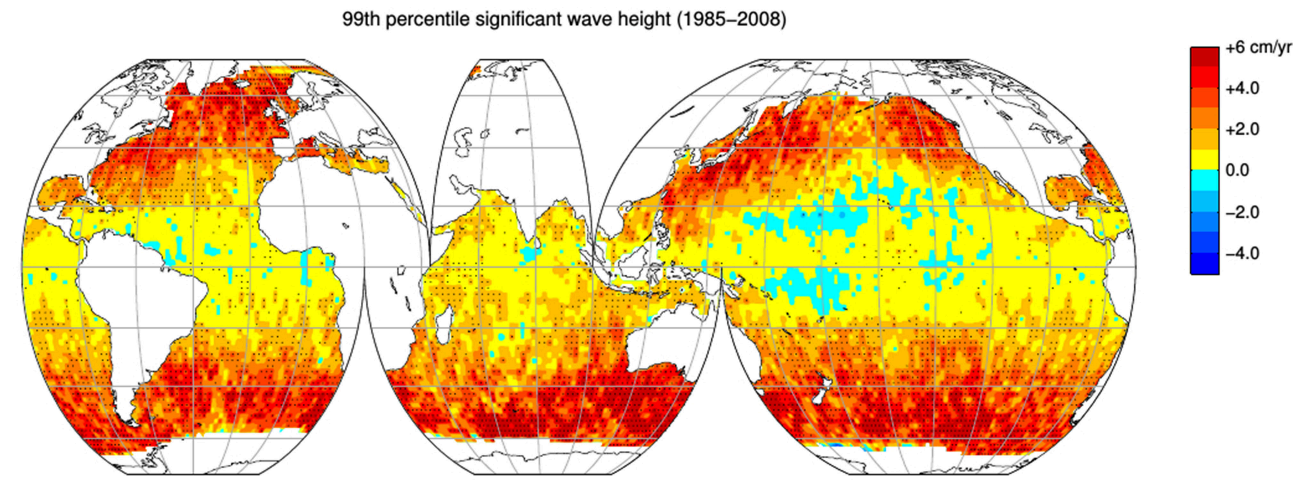

FIGURE 4 | H_S trends computed from a monthly time series of the 99th percentile from the merged altimeter database of Zieger et al. (2009) in 2° bins. The black stippling represents a statistically significant trend at the 99% confidence limit. reprinted from Young et al. (2011), as authorized by AAAS.

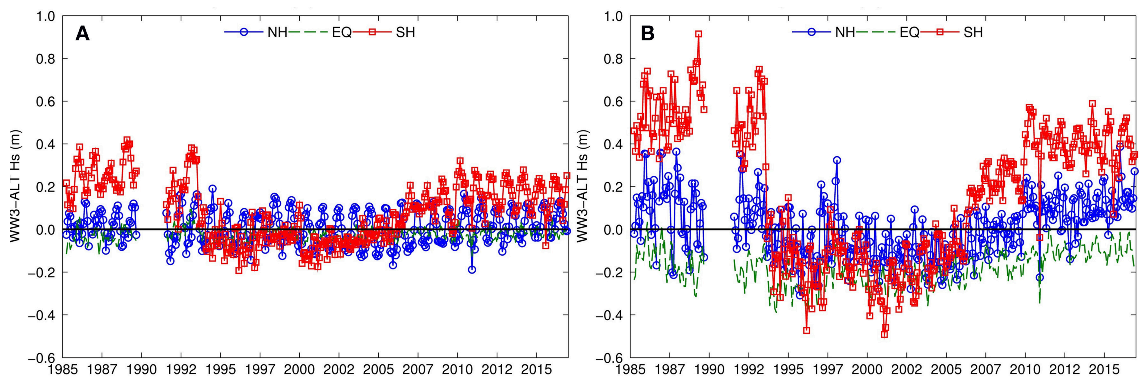

FIGURE 5 | (A,B) show H_S monthly median (50th percentile P50) and P95 residuals: wave hindcast forced by CFSR - altimeter. The statistics are computed for latitudinal bands: Northern Hemisphere (NH: latitude > 30°N), Equator (EQ: latitude < 30°), and Southern Hemipshere (SH: latitude > 30°S).

reference sites where other Essential Climate Variable (ECVs, see WMO, 2004) are measured. This is further discussed in section 4.

For open-water applications, the preferred wave measurement platform is a buoy. Buoys can be spherical, discus, spar, or boat-shaped hull. The most popular and widely used method measures buoy motion and converts the buoy motion into wave motion based on its hydrodynamic characteristics. Once the buoy response is determined for each hull, wave motion can be derived based on the buoy response function.

Directional buoy wave measurements based on buoy motion can be categorized into two types: translational (particle-following) or pitch-roll (slope-following) buoys. For both types, a variety of different sensor technologies is used to measure buoy motion. Since directional wave information is derived from buoy motions, the power transfer functions and phase responses associated with the buoy, mooring, and measurement systems play crucial roles in deriving wave data from buoys (Teng and Bouchard, 2005). This dependence is particularly important at low energy levels and at both short and long wave periods where the wave signal being measured is weak, and potential signal contamination increases.

All of the *in-situ* wave systems base their directional estimators on the measurements of three concurrent time series, which can be transformed into a description of the sea surface. All devices can provide good integral wave estimates (H_s, peak period, mean direction at the peak period, etc.). However, not all sensors can provide high quality "First-5" estimates because of the inherent inability of the sensor to separate wave signal from electronic and system/buoy response noise. This would degrade the quality of any derived directional wave spectra. In particular, high quality "First-5" observations can be used to resolve two different wave systems at the same frequency, if they are at least 60° apart, whereas other measurement systems cannot. Although there are more than five Fourier coefficients, the "First-5" variables provide the minimum level of accuracy required for a sufficiently accurate directional wave observing system, as it covers both the basic information (H_s, T_p, θ_m) along with sufficient detail of the component wave systems to be used for the widest range of activities. Going beyond the "First Five" requires an array of sensors (e.g., Krogstad, 2005), or imaging method based on radar or optical data.

As wave measurement systems continue to evolve, with changing hulls, composition, super-structures, moorings, sensors and on-board analysis packages, it is extremely important to maintain readily accessible metadata archives that continually update any change to a platform. Existing moored buoy networks are often legacy systems. Standardization of sensors, system configurations, or hull type would be costly and impractical, and not necessarily desirable. Continuous testing and evaluation of operational and pre-operational measurement systems is an essential component of a global wave observing system, equal in importance to the deployment of new assets. An overriding objective of continuous evaluation is to ensure consistent wave measurements to a level of accuracy that will serve the requirements of the broadest range of wave users. Comparisons of platforms and sensors have been pursued (Schwab and Liu, 1985; Skey et al., 1995; O'Reilly et al., 1996; Teng and Bouchard, 2005; Collins et al., 2014). These efforts are critically important because there were old designs, such as the NOMAD (Timpe and Van de Voorde, 1995) or 3-m discus buoys (Steele et al., 1992) being retired; and it is essential to relate the records of past wave climate, with hundreds of buoy years, to the present and future wave climates.

Another way to monitor the range of buoy hulls, sensors, and processing systems is to use radar altimetry from satellites as reference. This is particularly useful for buoys in open ocean and deep water and locations close to altimeter tracks. Queffeulou (2006) and Durrant et al. (2010) showed mean H_s differences of 10% between the U.S. NOAA-NDBC and the Meteorological Service of Canada (MSC) buoy networks by using the satellite altimeter estimates using as reference. Only part of this difference can be attributed to the fact that the satellite does not measure exactly the same region as the buoy, introducing a small bias and random difference (see also Krogstad et al., 1999).

In October 2008, a wave measurement technology workshop was held (JCOMM, 2008), with broad participation from the scientific community, wave sensor manufacturers and wave data users, following on from a March 2007 Wave Sensor Technologies Workshop (Alliance for Coastal Technologies, 2007). The overwhelming community consensus resulting from those workshops was that:

- The success of a wave measurement network is largely dependent on reliable and effective instrumentation.
- A thorough and comprehensive understanding of the performance of existing technologies under real-world conditions is currently lacking.
- An independent performance testing of wave instruments is required.

The workshops also confirmed the following basic principles:

- the basic foundation for all technology evaluations, is to build community consensus on a performance standard and protocol framework;
- multiple locations are required to appropriately evaluate the performance of wave measurement systems given the wide range of wave regimes;
- an agreed-upon wave reference standard (e.g., instrument of known performance characteristics, such as a particular model of the Datawell Directional Waverider series) should be deployed next to existing wave measurement systems for extended periods (e.g., 6–12 months, including a storm season) to conduct "in-place" evaluations of wave measurement systems.

in-situ wave observations also include waves visually observed from Voluntary Observing Ship (VOS), which provide the longest records of wave data worldwide effectively from the mid-nineteenth century. For certain applications (e.g., climate variability, extreme case studies) the length of record and/or near global coverage of VOS wave data make them more useful than other sources of wave information. One advantage of these data is that observational practices have not changed. All visual wave reports are included in the International Comprehensive Ocean-Atmosphere Data Set (Freeman et al., 2017), with wave information in 60% of the reports. The wave records are somewhat subjective since the wave observation accuracies are based on the skill and experience of the observer. Despite the potential subjective error, VOS wave climatologies are surprisingly consistent with wave hindcasts (Gulev and Grigorieva, 2006). In addition to observational uncertainties, VOS-based wave climatologies suffer from inhomogeneous spatial and temporal sampling. With regions far from shipping routes severely under-sampled such as the Southern Ocean and sub-polar Northern Hemisphere. These time and space sampling issues may significantly affect estimates of trends and inter-annual variability. VOS wave observations represent a substantial part of our knowledge about wind waves and should be further used and better validated. Beginning 1 July 1963 both sea (i.e., wind wave) and swell were reported. Prior to that date only the higher of sea and swell was reported. This makes the VOS data a unique source of such information (Gulev et al., 2003). Uncertainties in VOS wind wave heights are thoroughly described by Gulev and Grigorieva (2006) and Grigorieva and Badulin (2016). A VOS-based global atlas of wind waves (1970–2015) was recently updated, along with monthly means fields of wave parameters. It is available at https://sail.ocean.ru/atlas/.

As with any source of observational data, a comprehensive metadata record is essential to properly understand the wave information originating from the different platforms, payloads and processing systems. This is necessary to understand systematic differences in the measurements from differing observing networks, and for climate applications to ensure temporal homogeneity of the records to eliminate spurious trends. The IOC-WMO (International Oceanographic Commission-World Meteorological Organization) Joint

Commission for Oceanography and Marine Meteorology (JCOMM) has established an Ocean Data Acquisition System (ODAS) metadata standard, which is hosted at the China Meteorological Agency (ETMC, 2007). At a recent Regional Marine Instrumentation Center Workshop (February 2018), it was stated that, "Any measured data no matter the degree of accuracy, should be considered worthless if there is no corresponding metadata to define what and how the data were generated." (J.W. Swaykos, National Oceanographic and Atmospheric Administration-National Data Buoy Center, NOAA-NDBC, personal communication).

3.2. Challenges Using Existing *in situ* Wave Measurements

There are many challenges measuring wind-generated surface gravity waves from moored buoys that have a significant impact on the quality of the data. The Response Amplitude Operator (RAO) represents the mathematical transfer function of the buoy motion to an approximation of the free surface. Everything associated with the buoy (e.g., size, composition, super- and sub-structure, mooring), the sensor (and its relative location to the mean water level) and analysis package will alter the RAO. In general, the formulation of the RAO and testing provides adequate information to modify the mathematical form. In principle, all moored buoys measuring surface gravity waves would be considered as reference measurements.

Over the past decade, there is considerable evidence that the notion of "ground truth" has been violated. The directional response between buoys with different attributes (sensor, hull, mooring, processing) will result in differences in the higher moments of the directional parameters (O'Reilly et al., 1996; Teng and Bouchard, 2005), leading to misinterpretation of observations. For example, Bender et al. (2010) determined that H_s were overestimated by 56% in hurricane conditions, for the widely used method applied to a buoy with strapped-down 1D accelerometers. This is due to the mean tilt of the buoy due to high winds.

Besides the mean tilt, the instantaneous tilt has a small effect on the recorded shape of small amplitude surface waves (Collins et al., 2014). Before 2009, the vast majority of wave buoys in North America were based on strapped-down accelerometers. Since then, NOAA-NDBC modified their on-board packages correcting the error, but a large number of historical buoy records have not been corrected. **Figure 6**, shows a comparison of a gimballed (HIPPY™) sensor and a strapped-down (3DMG) accelerometer. Although the time series of the two sensors overlap in **Figure 6A**, the scatter and difference plot clearly indicate that the uncorrected H_s from the 3DMG, for over half of the data, are generally higher than values from the HIPPY™ sensor. This is particularly true for H_s over 6 m, with a 10% bias for H_s around 8 m.

As part of the DBCP Pilot Project on Wave Measurement Evaluation and Test (PP-WET; www.jcomm.info/WET), a field study evaluating the NOMAD (6N) was carried out in Monterey Bay from July 2015 through Oct 2018 (Jensen et al., 2015). The NOMAD buoy was equipped with five sensors, three from NDBC (Inclinometer, 3DMG-Motion Sensor, and a HIPPY™) and two from Canada (an MSC-Watchman™ and Wave Module, and a TRIAXYS™ Next Wave II Directional Wave Sensor). In addition, a NDBC 3-m aluminum discus buoy (46042) containing their standard 3DMG motion sensor and a HIPPY™ sensor was deployed as well as a Datawell Directional Waverider™ (DWR) used as the relative reference for all evaluations (Luther et al., 2013). These sensors gave typical differences of 0.25 m for an average 2.5 m wave height (Jensen et al., 2015).

In most if not all evaluations over the past four decades we have relied on the significant wave height, peak, mean period and more recently the mean wave direction. These, other than the peak period T_p, are integral parameters. For example, the significant wave height for the analysis here is based on the integration of the frequency spectra given by Equation (4). The integration masks where differences may occur in the shape of the spectrum $E(f)$.

WaveEval Tools, as described by Jensen et al. (2011) take a different approach. The four Fourier directional parameters are used to calculate the mean direction, spread, skewness and kurtosis (e.g., Kuik et al., 1988). Partitioning is performed on each discrete frequency band, and a discrete energy level. A bias and root mean square error percentage is determined from averaging the differences between two data sets. The result is a qualitative graphic displaying defined range of the per cent deviations. These techniques can provide useful information that is quantitative as well as qualitative reducing the assessment in directional properties to a reasonable number of products. Recently, two new methods have been proposed, evaluating frequency spectra (Dabbi et al., 2015) and correlating paired wave spectra (Collins et al., 2014).

There is no lack of trying to develop new methods to evaluate large spectral data sets to determine similarities, differences, quality or deficiencies in measurement to measurement systems, model to model results or model to measurements. However, we cling tightly to the bulk wave parameters because we know what they represent. For example two data sets produce a bias of 0.5 m out of 4 m. We know what that represents; we know how large a 0.5m H_s looks like. Now consider a difference in the frequency spectra of 10 m^2s out of 125 m^2s. The ratio is the same as in the case of the H_s, but what does it represent? That may be the only impediment holding the wave community back from progressing into the future. An intermediate solution is the use of partitions where we split a full spectrum into the single composing, and to a large extent independent, wave systems. Then the use of integral parameters makes more physical sense, and it is much more intuitive to mentally combine different and well defined wave systems coming together at the considered point.

Ensuring the quality of "First 5" data from present and future directional wave measurements would impact nearly every facet in the study of wind generated surface gravity waves from a physics based standpoint, to model improvements and daily performance of our weather prediction forecast centers. To have some quantifiable standard for all wave measurements would be highly beneficial to the user, and thus remove

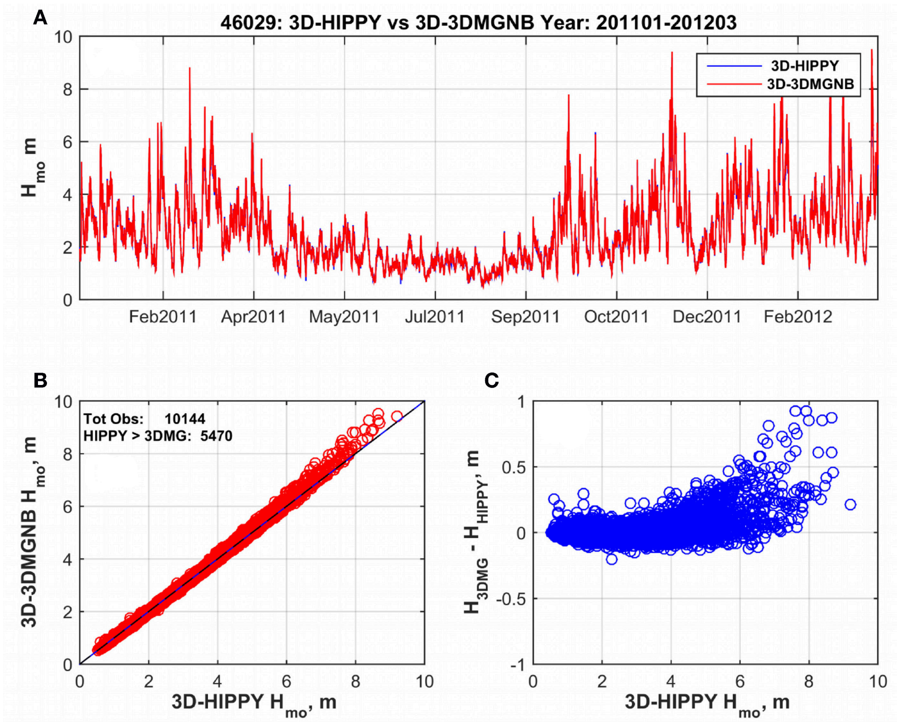

FIGURE 6 | Differences in H s for two sensors, a strapped-down 3DMG accelerometer, and a gimballed HIPPY sensor, mounted on the same buoy NDBC buoy 46029 (Columbia River Bar, Oregon) in a water depth of 134 m. **(A)** Shows time series from january 2011 to February 2012. **(B)** Shows 3DMGNB against HIPPY. **(C)** Shows the difference between the two as a function of wave height.

existing uncertainties, generally dismissed to the level where all data are at a uniform quality level, something far from the truth.

We should here mention other *in situ* measurement that may not comply with requirements but that are still used de facto, in particular when no other data source is available for delicate operations at sea. These include Ship-Borne Wave Recorders based on ship motions (e.g., Holliday et al., 2006; Nielsen, 2017) and X-band radar systems from Young et al. (1985) to more recent developments (e. g. Borge et al., 2004; Ma et al., 2015), and any combination of the two types of system. At present, very few datasets are available for the scientific community to make a detailed evaluation of the quality of these measurements. Their possible transmission on the Global Telecommunication System (GTS) of the WMO may promote a wider evaluation and use besides the need to have measurement at hand for real time decistion aid.

3.3. Satellite Remote Sensing

Routine measurements of sea states from satellites started with GEOSAT in 1985, with almost no interruption until today, except around 1990, as shown in **Figure 7A**. Over the years, different altimeters (solid bars in **Figure 7A**) supplied robust estimates of significant wave height (hereinafter H_s) and radar backscatter power related to the sea surface slope variance. Imaging radars have further given access to part of the directional wave spectrum (open boxes in **Figure 7A**).

A new type of instrument, called a ‘wave spectrometer’ by Jackson et al. (1985), was successfully launched for the first time on a satellite, on 29 October 2018, with the SWIM instrument on CFOSAT (Hauser et al., 2017).

While robust and often quite unique to inform about extremes (Young, 1993; Quilfen et al., 2006, 2011), satellite altimeter measurements suffer from a limited spatial sampling, and can easily miss particular events, as evident from the example daily coverage in **Figure 7B**. This is less of a problem for wave mode data from synthetic aperture radars (SARs), but present measurements mostly provide reliable directional estimates for very long swells, i.e., with periods larger than 12 s (220 m wavelength). Compared to buoy measurements, satellites can still provide a larger volume of data, thereby sampling more extreme sea states (Hanafin et al., 2012), to further enable the tracking of wave-related extreme events across ocean basins Collard et al. (2009).

Clearly, the number of observations evolves as new satellites are launched and others are decommissioned (**Figure 7A**). When considering the altimeter data averaged at 1 Hz (about 7 km along-track), each satellite mission accounts for approximately 1 million observations per month as shown in **Figure 8A**. Given the along-track noise, mostly related to retracking issues, and sea state large scale correlations, these estimates cannot be

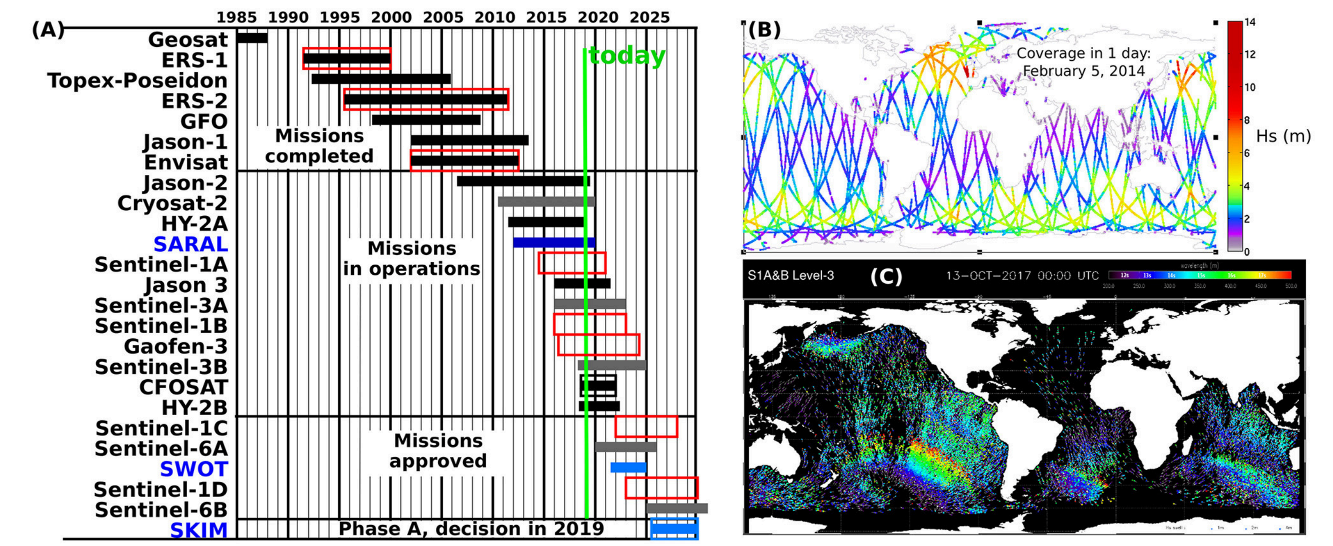

FIGURE 7 | (A) Time coverage of satellite missions from 1985 to 2030, including nadir and near-nadir altimeters (solid bars), and missions monitoring ocean wave spectra (open boxes) using C-band Synthetic Aperture Radars (red), and real aperture radars in Ku-band (black) or Ka-band (blue). The lighter color (gray and blue) bars correspond to altimeters using Delay-Doppler processing. Source: CEOS database http://database.eohandbook.com/). **(B)** example of 1-day coverage for Hs measurements with 4 satellite altimeters **(C)** snapshot of a "fireworks" plot, the height (size of symbols) peak periods (colors), and directions (barbs) of swell partitions derived from Sentinel-1A and Sentinel-1B wave mode data. Such plots are produced routinely by CMEMS.

considered independent. Moreover, the same region may often be sampled (in space and time) by two or more satellites, increasing the number of correlated observations.

Most climate studies typically compute wave statistics by binning satellite observations into longitude-latitude regions such as 1–2° bins (Challenor et al., 1991; Young, 1999). **Figures 8B–E** shows the number of observations in 2° bins for representative time periods. Because the number of altimeter observations changes throughout the time period, the statistics computed from these data could be affected by sampling biases. This is critical for both low and high latitudes that have less observations. In addition, sampling biases affect most strongly the tails of the statistical distribution meaning both extremely small and large wave heights are observed with less precision than the average sea state.

For SAR wave mode data, sampling biases could be even more critical because the datasets were relatively sparse. Now with Sentinel-1A and Sentinel-1B in orbit, the number of observations per month has increased 20-fold from a median of 3 rather small imagettes per 2 × 2° bin each month with ERS-2, to 60 big imagettes today, which add up to 120,000 wave mode products per month. Also, the quality of the Sentinel-1 data is incomparable.

3.3.1. Significant Wave Height From Altimeters

Most of the altimeters sample repetitive tracks covering a full cycle in 10–35 days, with the 10-day repeat giving a large spacing between tracks. The working principle of satellite radar altimetry is quite simple. Pulses reflected by the sea surface at nadir are recorded as a function of time. This travel time gives the distance between the instrument and that surface. The main objective is to precisely track the distance between the instrument and the mean sea surface. Echoes reflected back from a wavy sea surface are registered in time and assembled as radar power signals called waveforms. These waveforms then mimic the cumulative distribution function associated to the wave amplitude statistics, such as shown on **Figure 9A**. A peaked waveform will correspond to low-sea state condition. At variance, broad waveforms correspond to high sea state conditions. Waveforms are usually averaged, and formed at a rate of 20-Hz, corresponding to a sampling of about 300 m along the satellite track. Over the ocean, altimeter waveforms are then further characterized by a rising and falling shape. The rising part, the leading edge, integrates echoes from the wave crests, initially located near the nadir center point of the footprint (e.g., **Figure 9C**), to the wave troughs. The falling part, the trailing edge, then integrates non-nadir backscattered echoes, located away from the nadir point. The H_s estimates are then derived from the extent of leading edge, and typically averaged every 7 km along the tracks (the so-called 1-Hz sampling rate). The accuracy on H_s estimates then depends, among other things, on the range resolution dr, which is $dr = 0.30$ m for Ka-band SARAL and $dr = 48$ cm for all other ku-band satellite altimeters, as the ka-band instrument operates with a larger radar frequency bandwidth. Although measurements are usually attributed to a precise longitude and latitude, the energy of the leading edge corresponds to a footprint reaching over 10 km in diameter and the value of H_s is in fact a weighted average over this footprint.

A new generation of coherent radars can also use the phase of the radar echos. This allows a "SAR Mode" or "Delay-Doppler" processing that was pioneered with Cryosat-2 and is now used on Sentinel-3.

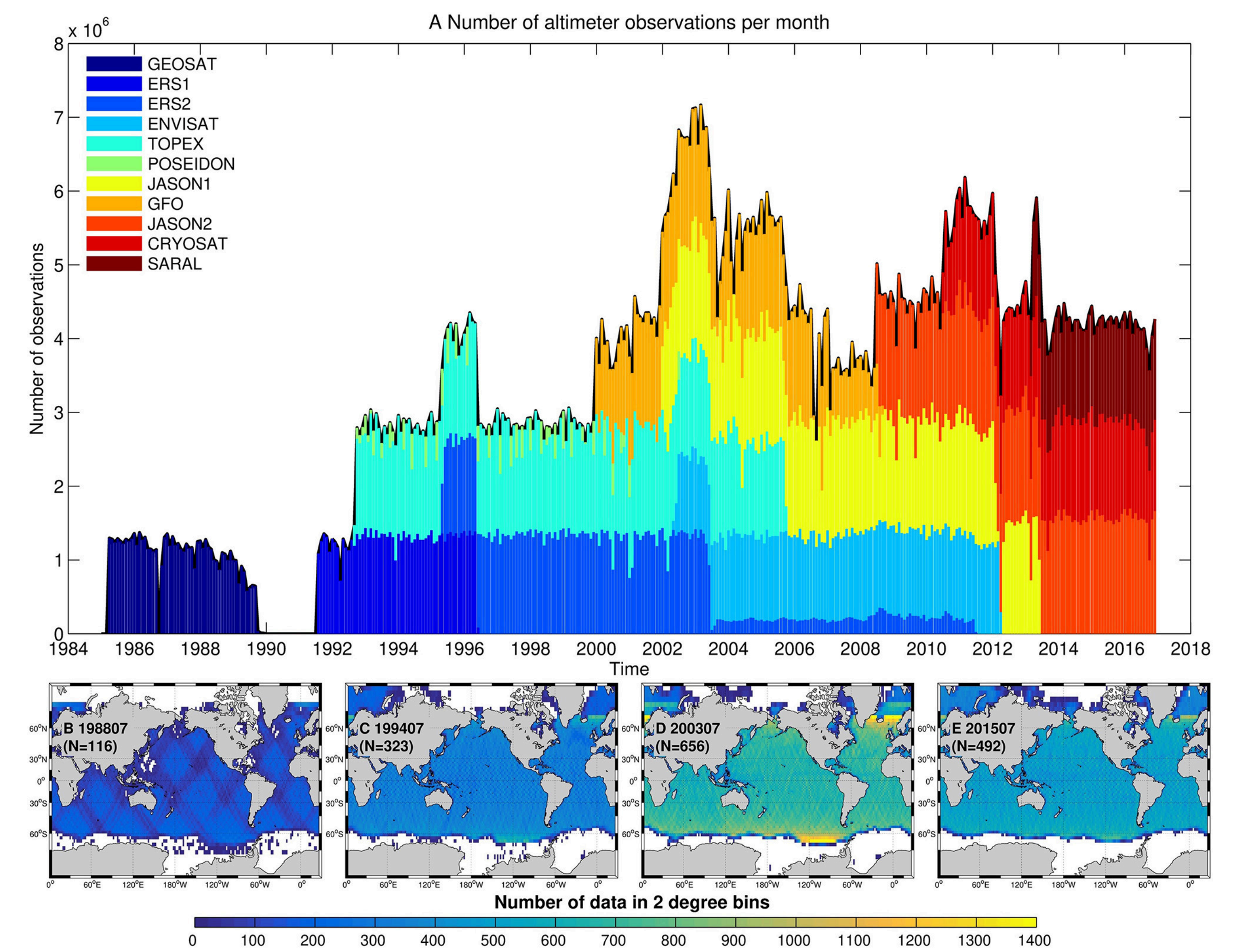

FIGURE 8 | Number of radar altimetry 1 Hz observations per month **(A)**. The lower panels show the number of observations in 2 × 2 longitude-latitude bins for July **(B)** 1988 (GEOSAT) **(C)** 1994 (ERS-1, Topex-Poseidon **(D)** 2003 (ERS-2, Envisat, Topex-Poseidon, Jason-1, GFO), and **(E)** 2015 (Jason-2, Cryosat-2, SARAL).

With delay only, the echoes are only distinguished by their time of arrival and each time window corresponds to an annular footprint on the sea surface (**Figure 9C**). In practice, most of the data contributing to the leading edge of the waveform come from a few range cells, that cover about half a significant wave height, i.e., for $H_s = 2$ m, the shape of the leading edge is determined by echoes from the first blue and white disks in **Figure 9C**. With the additional use of Doppler, the footprint can be separated in the along-track direction with "slices" (the black stripes in **Figure 9C**) that are typically 300 m wide (Raney, 1998; Scagliola, 2013). As a result, independent echoes acquired at different azimuth angles contain echoes from the same footprint "slice." It is customary to stack together these echoes, with an incoherent sum in order to create a multi-looked waveform with a much better signal-to-noise ratio (Raney, 1998).

Also, both trailing and leading edges of Delay-Doppler waveforms are sensitive to H_s (**Figure 9B**, see also Ray et al., 2015). The shape of the waveform is sensitive to other sea state parameters, such as the wave orbital velocity, that could be estimated. Because of the beam-limited asymmetrical SAR altimetry footprint, ocean waves with a wavelength of a few 100 m (swell and extreme wind waves) may, depending upon their direction, no longer be fully imaged within the instrument ground cells and therefore produce a distorted waveform shape (Moreau et al., 2018).

The parameter estimation in satellite altimetry is performed by a fitting process called retracking. At present, two different theoretical waveform shapes are used to fit the measured LRM and SAR waveforms, namely the Brown-Hayne model (Brown, 1977; Hayne, 1980) and the SAMOSA model (Ray et al., 2015). In terms of precision, we show in **Figure 9D** a representation of noise computed as standard deviation of the high-frequency H_s estimations within a 1-Hz along-track separation, since the variation measured by the altimeter

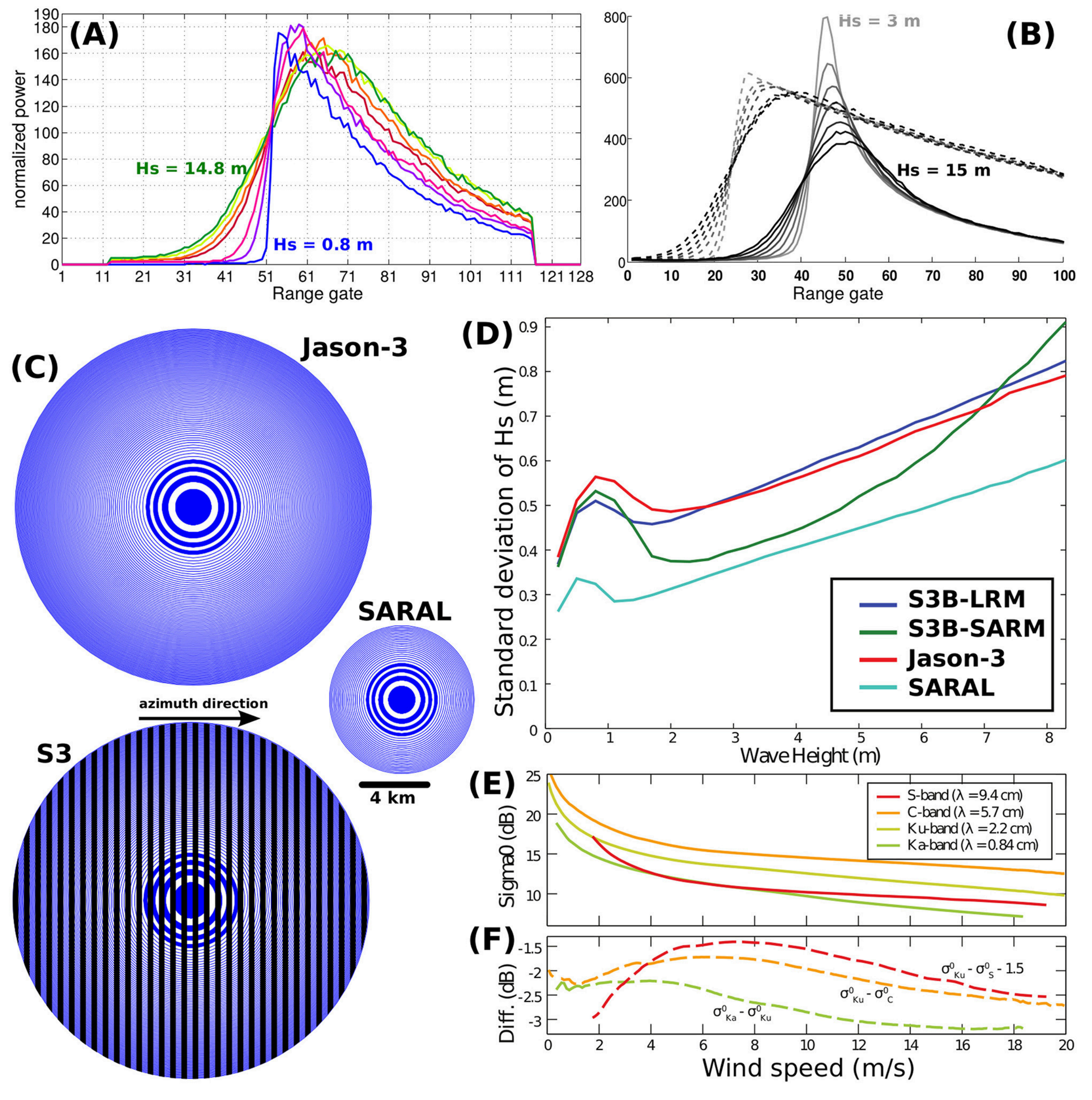

FIGURE 9 | (A) Example of waveforms for a pass along the ascending track of SARAL/AltiKa on February 5, 2014, between 05:29:49 and 06:20:07 UTC. Each waveform shows the power measured by the radar as a function of time: time is discretized with intervals of 2×10^{-9} s corresponding to 30 cm range intervals usually called "range gates." The corresponding wave heights are 0.8, 3.2, 4.6, 9.7, 10.7, 13.2, and 14.8 m. **(B)** averaged SARM (solid) and LRM (dashed) waveform from Sentinel-3 for H_S = 3,5,7,9,11,13 and 15 m, for cycle 23 orbit 349, on 25 October 2017 in the Pacific **(C)**. Typical size of footprints on the ground for Jason-3, SARAL, and Sentinel-3, as limited by the radar antenna pattern. The rings with alternating blue and white filling, correspond to iso-range lines on a hypothetical flat surface. Only the first few rings are filled for readability. For Sentinel-3 the vertical bands show the azimuth resolution. **(D)** High-Frequency Noise on H_S, computed as Standard Deviation (SD) of high-frequency measurements within a 1-Hz along-track separation, with respect to H_S. Data are averaged for a full cycle of Jason-3, SARAL, Sentinel-3B LRM Mode (S-3B LRM, used in 13 days of cycle 10) and Sentinel-3B SAR Mode (S-3B SARM). **(E)** Backscatter strength (σ^0) as a function of wind speed, and **(F)** differences for different radar frequencies, adapted from Quartly (2015), as authorized by Taylor & Francis.

within 7 km is dominated by noise. The improvement of SAR altimetry compared with LRM altimetry is evident, except for at low and high sea states. Currently, the only Ka-band altimeter mission (SARAL, also known as AltiKa) has the lowest noise level, as shown in **Figure 9D** thanks to a smaller footprint and a higher number of pulses. The actual accuracy of these measurements is usually assessed by means of comparison with models and *in situ* data (e.g., Passaro et al., 2015; Sepulveda et al., 2015).

For coastal, near-ice or high resolution applications, altimetry is limited by the size of the footprint which can be contaminated by non-Gaussian surfaces such as land and ice, and the noise of the H_s estimates. Typically, LRM altimetry performs poorly at distances up to 20 km from the coast (Passaro et al., 2015). The smaller footprint of SAR altimetry and SARAL-Altika reduces this problem (Hithin et al., 2015; Dinardo et al., 2018). As for noise, it can be reduced by improving on the tracking methods (Passaro et al., 2015; Ardhuin et al., 2017a) and filtering the data (Quilfen et al., 2018). Other altimeter limitations involve low sea states, because the leading edge is poorly discretized, giving a large relative uncertainty in the estimation of H_s for $H_s < 1$ m (Smith and Scharroo, 2015), and rainy conditions, with stronger impacts as the altimeter frequency increases (e.g., Quilfen et al., 2006; Tournadre et al., 2015).

From these waveforms, the primary focus is the retrieval of the sea level, which is usually called "epoch" in that context, i.e., the time-distance between the instrument and the mean sea surface. As understood, backscatter echoes mostly correspond to specular local conditions as function of the surface wave elevation profiles. The epoch, and thus the derived sea level estimates, are then likely biased, as reflected radar signals are stronger in the troughs than near the crests of the waves. The bias is then written as $h_b = \overline{h.\sigma}/\bar{\sigma}$, with h local surface elevation, σ local radar backscatter signals. This bias is then often corrected by directly using H_s, and the total mean backscatter coefficient $\bar{\sigma} = \sigma^0$, estimated from the waveform maximum.

3.3.2. Surface Roughness and Wind Speed From Altimeters

The other key parameter derived from the retracking process is the maximum amplitude of the radar echo, denoted by the normalized backscatter coefficient, σ^0. This is primarily related to the statistics of surface slopes (Nouguier et al., 2016), usually summarized by the mean square slope (mss), which is primarily dependent upon the near surface wind speed at 10 m elevation, U_{10} (Cox and Munk, 1954; Bréon and Henriot, 2006). Yet, second-order effects, diffraction, curvature, and/or non-Gaussian effects can still be traced, especially when directly comparing coincident altimeter measurements performed with differing operating frequencies, i.e., C-band and Ku-band for TOPEX and the JASON instruments (Chapron et al., 1995; Elfouhaily et al., 1998; Tran et al., 2006).

Accordingly, there is no clear functional form that is appropriate to connect U_{10} to the mss, as the wind is not the only factor defining the mss. Although there is a very strong correspondence between wind speed and σ^0, other factors certainly contribute to the measured backscatter. For instance, Vandemark et al. (1997) examined relationships between altimeter backscatter and the magnitude of near-surface wind and friction velocities, with improved agreements found after correcting 10-m winds for both surface current and atmospheric stability. More importantly, Elfouhaily et al. (1998) and Gourrion et al. (2002), and Golubkin et al. (2015) showed that σ^0 strongly responds to the sea state degree of development. Using the H_s altimeter estimates as an indicator of the sea state degree of development, wind estimates can be improved, in particular now that the noise of H_s and σ^0 estimates can be reduced following Sandwell and Smith (2005) and Quilfen et al. (2018). This is limited to not too young sea states, otherwise the same pair of measurements (σ^0, H_s) can correspond to two pairs of sea states (U_{10}, H_s) with very different wave ages (Farjami et al., 2016).

As an alternative analysis strategy, it has been demonstrated that with increasing wind speeds, the dual-frequency data provide a measurement more directly linked to the short-scale surface roughness (Chapron et al., 1995), which in turn is associated with the local surface wind stress (Elfouhaily et al., 1998), and gas transfer (Frew et al., 2007). The dual-frequency data also highlight the effect of rain on the perceived signal (Quartly et al., 1996).

Finally, Vandemark et al. (2016) demonstrated that sea surface temperature also modulates σ^0 through its effect on the emissivity of water, and Quartly (2010) showed that, for the TOPEX and Jason satellites, there are unexplained oscillations in recorded σ^0 associated with changing solar illumination of the spacecraft. Most of these factors are ignored in current operational wind speed algorithms.

We note that there is significant uncertainty about the absolute calibration of σ^0 for all past and present altimeters. Efforts to produce an absolute calibration for σ^0 from Envisat using calibrated on-ground transponders still had an uncertainty of 1 dB (Pierdicca et al., 2013), whereas the required tolerance for climate studies necessitates knowing the drift to better than 0.03 dB/decade. Thus, in practice, all current wind speed algorithms are empirical, based on matching up altimeter observations of σ^0 with a host of meteorological buoys and instruments on ships or other platforms of opportunity.

Without absolute calibration, considerable efforts are thus directed to align σ^0 observations from one mission to a predecessor on the same orbit, the integrity of the climate record rests on the buoys and models used for long-term monitoring of instrument performance. In particular, there is not even an agreed universal scale for σ^0 data, with the values recorded by two Ku-band altimeters differing by an offset of more than 2 dB. Furthermore, as mentioned above, there is no simple adjustment between normalized backscatter observations at one radar frequency with those at another (**Figures 9E–F**), because each is responding to a different scale length of sea surface roughness as illustrated by **Figures 9E,F**. Since there have been more than 30 years of Ku-band and C-band altimetry, the launch of SARAL operating only at Ka-band, necessitated a new specific effort to produce relevant wind speed algorithms (Lillibridge et al., 2014; Quartly, 2015).

Global analyses of the joint altimeter measurements of H_s and σ^0 related U_{10} show that the majority of the ocean is dominated by swell (Chen et al., 2002). These combined metocean records then further invite other parameters to be developed either theoretically or empirically, such as pseudo wave age (Glazman and Pilorz, 1990) and wave period (Gommenginger et al., 2003; Mackay et al., 2008).

3.3.3. 2D Wave Spectra Monitoring With Synthetic Aperture Radars and Other Imagery

Synthetic aperture radars (SARs) are coherent microwave radars that measure the sea surface roughness and Doppler at very high resolution, using the Doppler frequency to achieve a high resolution in the satellite flight direction (known as azimuth), of the order of 5 m depending on the instrument acquisition mode. Remote sensing with SAR has then been generally focused on land (ground deformation, subsidence ...) and sea ice applications (Kwok et al., 1990). Indeed, such a fine resolution capability can only be achieved provided the target can be considered as frozen during the integration time of the order of 0.5 s. In practice, over the ocean, orbital motions of high frequency waves cannot be neglected and can strongly degrade the azimuth resolution to a couple of 100 m, depending on the sea state (Kerbaol et al., 1998; Stopa et al., 2015). Accordingly, the SAR azimuth response mirrors the probability distribution of the radial velocity component of the scatters and causes the azimuth resolution to be proportional to the root mean square orbital motions of the high frequency waves. Wave components with wavelengths larger than the azimuth cutoff have constructive velocity bunching while waves with shorter wavelengths have destructive velocity bunching and are strongly distorted. Therefore, swells are often well resolved by SAR and are consistent with *in-situ* buoy observations (Collard et al., 2009).

Still, over oceans, SARs are unique in providing all-weather very high resolution imagery of a wide variety of oceanic and atmospheric phenomena. Mature ocean applications include the measurement of winds at high resolution (e.g., Mouche et al., 2017), and ocean waves. In particular, the ERS-1, ERS-2, Envisat, Sentinel 1 and Gaofen-3 satellite include a default "wave mode" for acquisition over the oceans that allows the routine mapping of wave properties over large scales (Hasselmann et al., 2012).

In the open ocean, the processes that explain the formation of wave patterns in a SAR image, such as **Figure 10**, are fairly complex and can be quite non-linear (Hasselmann et al., 1985; Tucker, 1985; Alpers and Bruening, 1986; Holt, 1988; Hasselmann and Hasselmann, 1991). Yet, the unique capability to possibly capture directional wave properties, in particular the part associated with long swells (Lehner, 1984) means that a sparse coverage of the ocean is enough to observe full swell fields, as shown in **Figure 7C** (Collard et al., 2009).

A wide range of methods have been developed to retrieve wave information from SAR imagery, with important contributions from Engen and Johnsen (1995) who introduced multi-look formation from Single Look Complex image that allows one to reduce the noise in the spectra and lift the 180° ambiguity in wave propagation direction. Both aspects are used in the quasi-linear spectrum retrieval algorithms (Chapron et al., 2001b; Johnsen and Collard, 2004) that form the basis of the ESA level-2 products for wave mode data. In practice the ambiguity removal may fail to pick the right direction, which explains why a few arrows point west instead of east in **Figure 10**. As mentioned above, the precision of SAR wave parameters has been assessed from 2D spectra comparison between buoy observations and SAR spectra (Collard et al., 2009). Precision is low for environmental conditions with strong distortion from the azimuth cutoff effect (e.g., storms). However, in the far field, emitted swells are well captured, leading to consistently observe basin-scale swell patterns by using the space-time consistency swells (e.g., the fireworks in **Figure 7C**, see also Collard et al., 2009).

To complement retrieval algorithms, empirical methods have been proposed for SAR to more directly estimate H_s from σ^0 mean and normalized variance estimates. At first, an original technique, called CWAVE, was developed for ERS-2 by Schulz-Stellenfleth et al. (2007). Specifically, CWAVE uses σ^0, the normalized variance of radar cross section, and 20 other orthogonal statistics computed from the image modulation spectrum to empirically estimate H_s. CWAVE was re-calibrated for ENVISAT (Li et al., 2011) and Sentinel-1 (Stopa and Mouche, 2017). As retreived, H_s exceeding 9 m are consistent with numerical models and radar altimeter estimates in extra-tropical storms and tropical cyclones (Stopa and Mouche, 2017). Therefore, the SAR technology can estimate waves in environments where the standard approaches to estimate directional wave spectral property from the image spectrum typically perform poorly. CWAVE is adaptable to estimate other sea state parameters such as wave energy and wave period, but the precision is reduced compared to H_s (Schulz-Stellenfleth et al., 2007; Stopa and Mouche, 2017).

Finally, optical imagery, even if they cannot offer a full global monitoring for all seasons due to particular observation constraints (cloud cover and sun zenith), are unique in their resolving capability with, for example all coastal areas covered by Landsat and Sentinel 2A and 2B satellites. Sentinel-2 capability to precisely estimate the full directional wave spectrum has been demonstrated by Kudryavtsev et al. (2017), and is further discussed by Villas Bôas et al. (2019). This unique capability is taking advantage of the different parallax angles between the 12 adjacent detectors used to cover the 280 km swath at 10 m resolution. This slightly different viewing geometry is used to estimate the transfer function between brightness variations and slope variations. Additional information on the wave dispersion and current velocity can then be quite uniquely extracted from the different sensing time (up to about 2 s) of the same point on ground by different channels within each detector, having also slightly different viewing angles. These enhanced capabilities certainly open new possibilities to combine different satellite measurements (including SAR and altimeter measurements) and possibly provide validation opportunities for upper ocean motions, including surface currents and its gradients, and waves. Recent airborne demonstrations by Yurovskaya et al. (2018) show that daylight sea state monitoring with drones is already feasible.

3.4. Other Observations: Microseisms

Among the many other measurements that contain a signature of sea state, a special mention should be given to the background noise recorded everywhere on Earth, and known as microseisms.

Microseisms are the dominant signal in seismometers. The strongest microseisms have periods around 4 to 10 s, and are generated when waves with similar frequency travel in

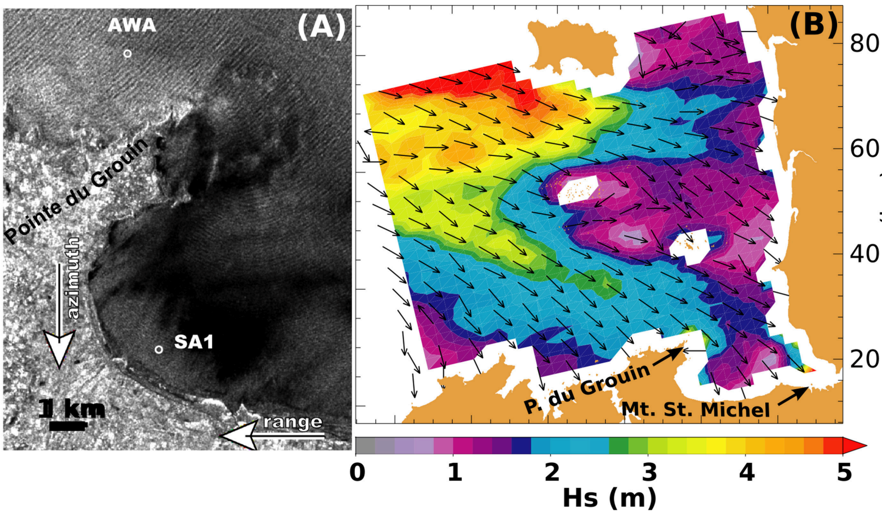

FIGURE 10 | (A) extract from an Envisat IW mode image, March 2003 (see Collard et al., 2005) and **(B)** map of wave heights and mean direction estimated from the Single Look Complex image.

opposing directions (Longuet-Higgins, 1950; Hasselmann, 1963) and microseisms have a frequency doubled compared to that of the ocean waves. This generation of seismic waves is particularly amplified in deep water and vanishes in shallow water (Ardhuin and Herbers, 2013), with vertical ground motions of a few micrometers that correspond to seismic Rayleigh waves. The sea states that are most effective for generating microseisms can be classified is three broad classes, and include, is order of magnitude, the generally broad directional spectrum at high frequency, the effect of coastal reflection, and the collision of two wave systems from different storms (Ardhuin et al., 2011).

The signal around 7 s is so clear, that seismic stations were set-up in the late 1940s to detect and track hurricanes (Gutemberg, 1947), and were used on the U.S. west coast in the 1970s to measure ocean waves (Zopf et al., 1976). With ocean buoys and satellites available, using microseisms for sea state application may sound outdated. Still, seismic records are unique in their sensitivity, being able to pick-up swell fore-runners of amplitudes under 0.1 m (Husson et al., 2012), and covering many regions of the world for which, before CFOSAT, there was no measurement of wind sea spectra (e.g., Barruol et al., 2006).

Following Zopf et al. (1976), and using data from the Berkeley seismic station (BKS) in California, Bromirski et al. (1999) showed how one may reconstruct a time series of ocean wave spectra from the seismic spectra of a nearby land station. This was further explored by Ardhuin et al. (2012), as shown in **Figure 11A** for the year 2008, using a power law relation estimated from the first 20 days of the year (shaded gray). Although there is a clear correlation between wave heights and microseism amplitude, the relation between the two varies because microseism amplitudes are the product of the amplitude of the wave trains traveling in opposing directions. When, the opposing waves are generated by coastal reflection, this gives one particular relation, but when the opposing waves are due to two uncorrelated wave systems, this typically gives a very strong noise, with a very weak correlation to the wave height (e.g., Obrebski et al., 2012; Butler and Aucan, 2018). One may use a wave model with or without wave reflection at the shoreline to probe this effect, and clearly, all the outliers in **Figure 11B** are caused by events unrelated to shoreline reflection.

Another important question when estimating wave parameters from microseisms is the location of the sources in the ocean. In the case of California, a direct modeling of the seismic sources suggests that 50% of the sources, on average, are located withing a 800 km band of ocean along the California coast, with water depths over 300 m. This is highly dependent on seismic propagation and attenuation, and other sites, such as Hawaii or the Tuamotus are sensitive to sources over a much wider region. It is thus difficult in general to estimate wave height at a single location from a single seismic station, and one may use multiple stations (Möllhoff and Bean, 2016) or a coherent processing of station arrays that can use seismic body waves instead of surface Rayleigh waves to locate the seismic sources (Gerstoft et al., 2006; Obrebski et al., 2013; Meschede et al., 2017).

Instead of trying to invert the signal, one may use a forward model from wave spectra to the seismic signal. This is made difficult by the poor knowledge of wave reflection at the shore and seismic wave propagation for these periods (Ying et al., 2010; Gualtieri et al., 2015). Still, the correlation between modeled and measured seismic ground displacement is usually very high, suggesting that seismic data could be assimilated to correct the wave model, its forcing, or the seismic propagation model. **Figures 11E,F** show observed and modeld microseisms at the Grafenberg array in the south of Germany, with numerical data available since 1976, and the Uccle station in Brussels, Belgium, where instruments have been recording since 1898.

One of the greatest interests in microseisms arises from the long term time series that can be obtained. Bernard (1981,

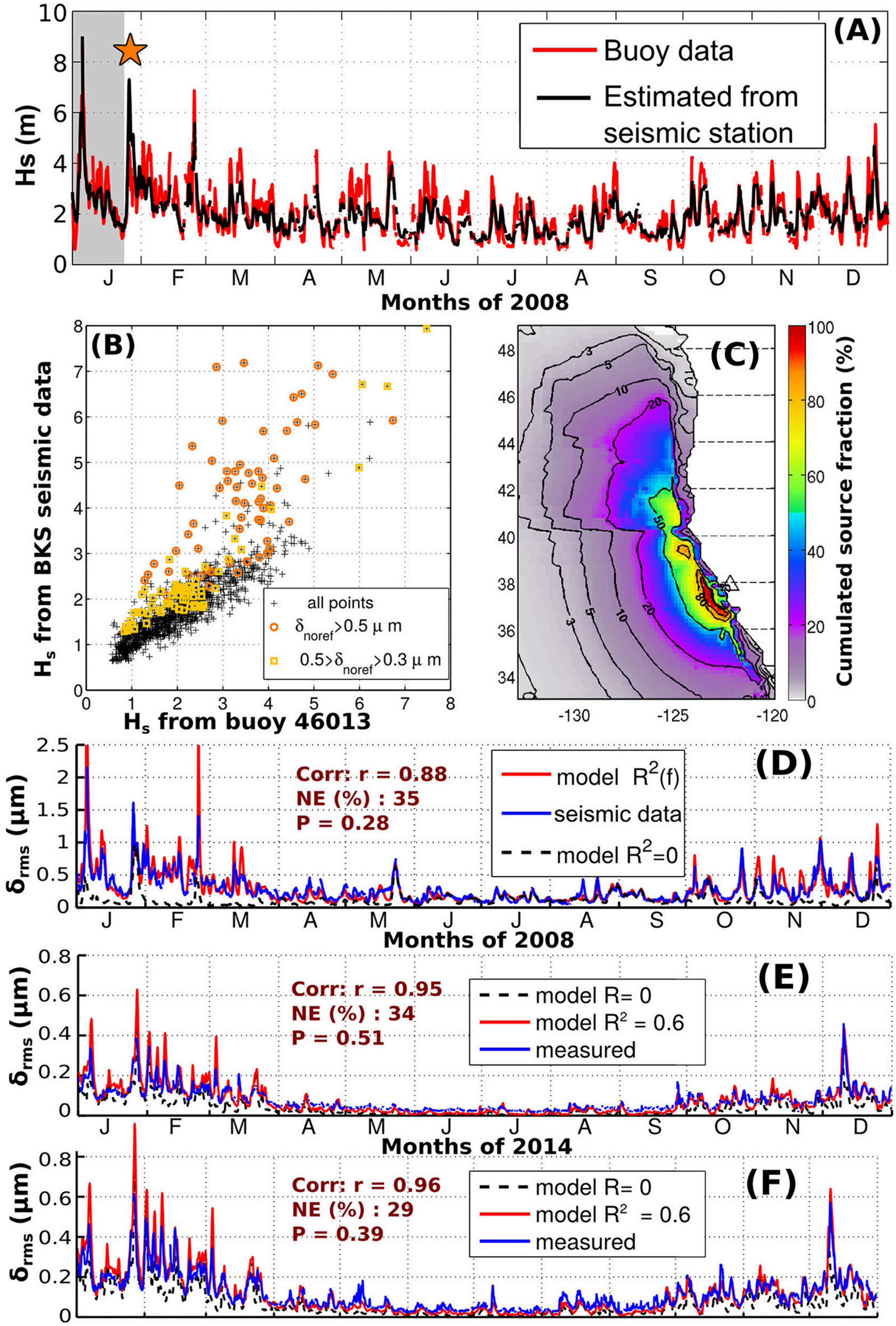

FIGURE 11 | (A) Measured wave heights at buoy 46013 and estimates from the BKS seismic station. The star marks a particular event on January 26 with microseisms generated by oposing wave trains from two distinct storms. **(B)** Correlation between measured and estimated wave heights, highlighting the outliers unrelated to coastal reflections **(C)** Average spatial distribution of microseism sources recorded at the BKS seismic station (triangle). **(D–F)**: modeled and measured microseism amplitude at stations BKS, station 4 of the Grafenberg array (Germany), and Uccle (Belgium). Model results are shown with or without coastal reflection to give a sense of the uncertainty of the simulation and of the importance of the wave energy reflection coefficient, which is set here at 6, 12, and 24% for continents and large islands, islands smaller than 50 km, and icebergs, respectively.

1990) made early attempts at studying the wave climate from microseisms, analyzing data between 1910 and 1975 from 12 seismic stations, mostly located around the North Atlantic. His 2-year averaged relative microseim amplitude oscillated between 0.8 and 1.2 without any clear trend but near-decadal oscillations. Bernard attributed these oscillations to an influence of the 11-year sun cycle on the storms, where a modern reader would rather see the pattern of the North Atlantic Oscillation. More recently, Grevemeyer et al. (2000) estimated a "microseism index" from the Hamburg seismic station, which increased 4-fold between 1955 and 1995. They linked that trend to a trend in wave heights measured at Seven Stones (off the southwest coast of the UK), which increased by 20% from 1960 to 1985. Such trends are not compatible with other seismic data analyses (e.g., Aster et al., 2008), highlighting the difficulty of estimating stable amplitudes from different instruments spanning over a century of seismic monitoring.

Besides the main microseism peak, Other signals are recorded at longer periods, which are well explained by the interaction of waves with a sloping bottom, and microseisms are generated at the same frequency as the waves, in the primary microseism band, 10–20 s (Ardhuin, 2018), and in the hum band, 30–300 s (see Deen et al., 2018). These other bands can also be used to constrain sea states, including infragravity waves.

4. FUTURE OF SEA STATE MEASUREMENTS

4.1. *In situ* Observations

Here we focus on the major *in situ* wave measurement centers, defined as those transmitting to the Global Telecommunication System (GTS) of the WMO in real time, i.e. within 1–3 h from the measurement. Data that do not make it on to the GTS do not exist for most applications, we will come back to this. These centers have faced with an increase in operation and maintenance costs, not to mention an increase in vandalism. Meeting the needs of users such as Numerical Weather Prediction Centers, researchers and developers of new wave modeling technologies, continuation of long-term records in the investigation of climate trends, has become a challenge.

Unfortunately, support for network expansion, upgrades to existing platforms to measure directional information, has so far been deemed by the agencies responsible for wave measurement to be too costly, in spite of the previous recommendations (Swail et al., 2009). Instead, these agencies have focused on trying to reduce costs in various ways.

Fortunately, and very timely, technological advances since OceanObs'09 with respect to wave measurement have been extremely prolific, especially with regard to high-quality sensors, but also with platforms and real-time transmission. Rather than simply decommissioning existing assets (i.e., reducing the number of buoys), there has been a transition toward the replacement of large buoys (e.g., 12 m, 10 m, NOMADs) and migration of 3 m aluminum hulls to smaller foam-based buoys with even smaller discus hulls with diameters 1.8, 2.3, 2.4, and 2.1 m (Hall et al., 2018). These new platforms minimize the need for large vessels, and increase the number of buoys able to be transported during a scheduled cruise. Wave measurement sensors have migrated to small computer chip systems (Teng and Bouchard, 2005; Teng et al., 2009; Riley et al., 2011). With the advent of the smaller hulls, improved battery packs, less power required and new compact sensor packages, changes are being made to the super-structure configuration of NDBC buoys as shown in **Figure 12**. Also, Datawell is now manufacturing its buoys with different hull diameters. While the smaller hulls are easier to deploy and better suited for shorter wave periods, it should be noted that these buoys have different responses (Datawell, 2014).

We note that the motion sensor in many of new NDBC configurations such as in **Figure 12B** is located well above the mean water level, whereas historically (**Figure 12A**) that sensor is placed inside the hull at the water level. Foam composition buoy hulls are much lighter than NDBC's standard 3m aluminum hull. As previously mentioned, the RAO (transfer function of the buoy motion to the free surface) has to be quantified for the hull weight, super-structure modification, and also the sensor location. If properly formulated and evaluated through laboratory and field testing the quality in the new buoy systems should be as accurate as has been found historically.

Also, GPS velocity measurements have been used to estimate the wave conditions from small buoy systems (Vries et al., 2003; Herbers et al., 2012; Thomson, 2012; Reverdin et al., 2013; Centurioni et al., 2018, 2019; Guimaraes et al., 2018). The buoy velocities are determined in a fixed frame of reference from the external GPS signals eliminating the need for calibration of an on-board motion-sensor or compass. This reduces the size and cost, so that it can be mounted in very small hulls. One of the drawbacks of the GPS measurement approach is that the communication relies on a satellite link that could be disrupted by large wave conditions or submerged from breaking waves. Despite this shortcoming, these systems would have the potential for the expansion of the world's wave measurement array at limited cost.

Wave measurements from the small GPS drifters can have a significant impact on our ability to observe the world's oceans that would parallel existing and new generation satellite-based remote sensing systems. The equipment of just 10% of the existing drifter buoys (cyan symbols in **Figure 13B**) with high-quality directional wave measurement systems, would have a great impact for Numerical Weather Prediction, the evaluation of numerical wave models, ship routing, and early warning for tropical cyclone or remote swell impacts that are a dominant flooding hazard in some regions (Lefèvre, 2009; Hoeke et al., 2013). A similar extension of wave measurement to moored buoys in the tropics would also greatly contribute to the understanding of air-sea fluxes (Cravatte et al., 2016). Further, there are substantial gaps in the Coastal Buoy Network (red symbols in **Figure 13B**, see **Figure 13A** for those reporting wave measurements on the GTS). Although, the addition of many more coastal stations is doubtful in the near future, the amount of data could easily be doubled if the

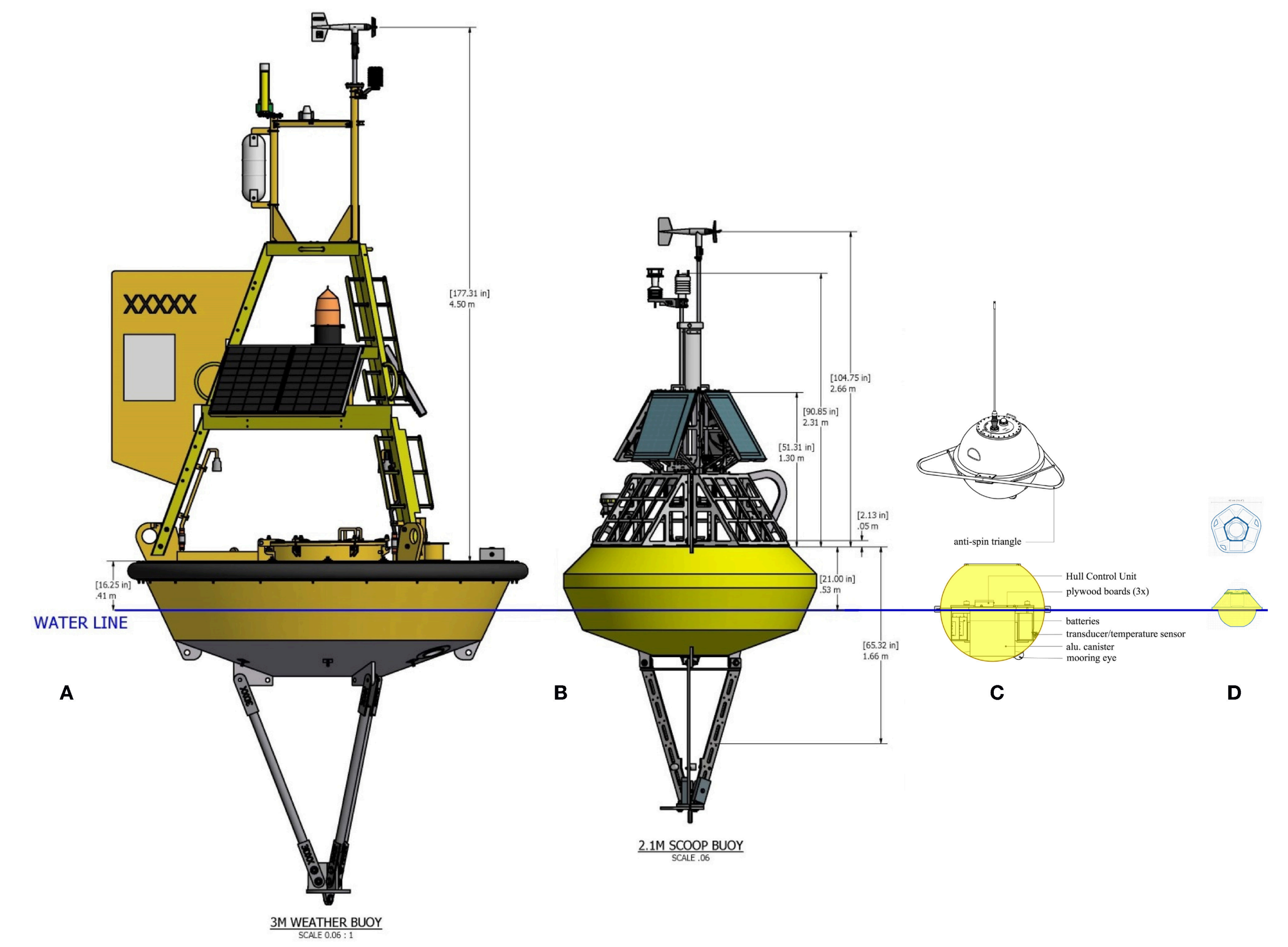

FIGURE 12 | Schematics of existing and planned super-structures of NDBC moored buoys measuring waves, (credit Eric Gay, NDBC). **(A)** is the standard design of 3-m discus buoys (Steele et al., 1992) pictured in **Figure 1A**, **(B)** is the new SCOOP design with a 2.1 m diameter that is replacing many buoys. The 3-m diameter SCOOP is pictured in **Figure 1B**. For reference, **(C)** is the schematic for the Mark 4 Datawell waverider with a 0.9 m hull diameter, drawn to scale, and **(D)** is the schematic of a Spotter buoy made by Spoondrift, following the developments of Herbers et al. (2012).

organizations in charge of collecting wave data could transmit it over the GTS.

The proliferation of low cost, high-quality directional wave sensors in the past few years, coupled with the increased use of smaller hulls has greatly reduced the cost of wave measuring systems, so that the entire moored buoy networks could eventually be transformed to the "First-5" directional measurement capability at a lower cost than existing networks. New technologies are continually being developed which may also come into play over the next decade, including the possibility of high-quality measurements from gliders (Daniel et al., 2011), stereo video (Fedele et al., 2013; Benetazzo et al., 2017), or lidar scanning (McNinch, 2007). These last two techniques have already proven very useful for wave research and may find a broader community of users with the continued decrease of processing and instrument costs.

4.2. Remote Sensing

As listed on **Figure 7**, the very large increase in the number and capabilities of new satellite missions that we have seen over the past decade will likely continue, with very important innovations in terms of instruments and concepts. Starting with altimeters, the revolution of Delay-Doppler altimetry is ongoing, and these have yet to be fully exploited, probably allowing the estimation of more parameters, including a more direct measurement of the mean period $T_{m0,2}$. The Surface Water Ocean Topography mission (SWOT, Morrow et al., 2019) is due for launch in 2021. It is primarily designed to measure the water level of sea, rivers and lakes but it is very sensitive to waves, and will thus add particular estimates of wave orbital velocity and wave height across its 120 km wide swath. SWOT is in fact a SAR with near-nadir incidences that will provide unprecedented measurements of surface currents and their small scale gradients, which are very

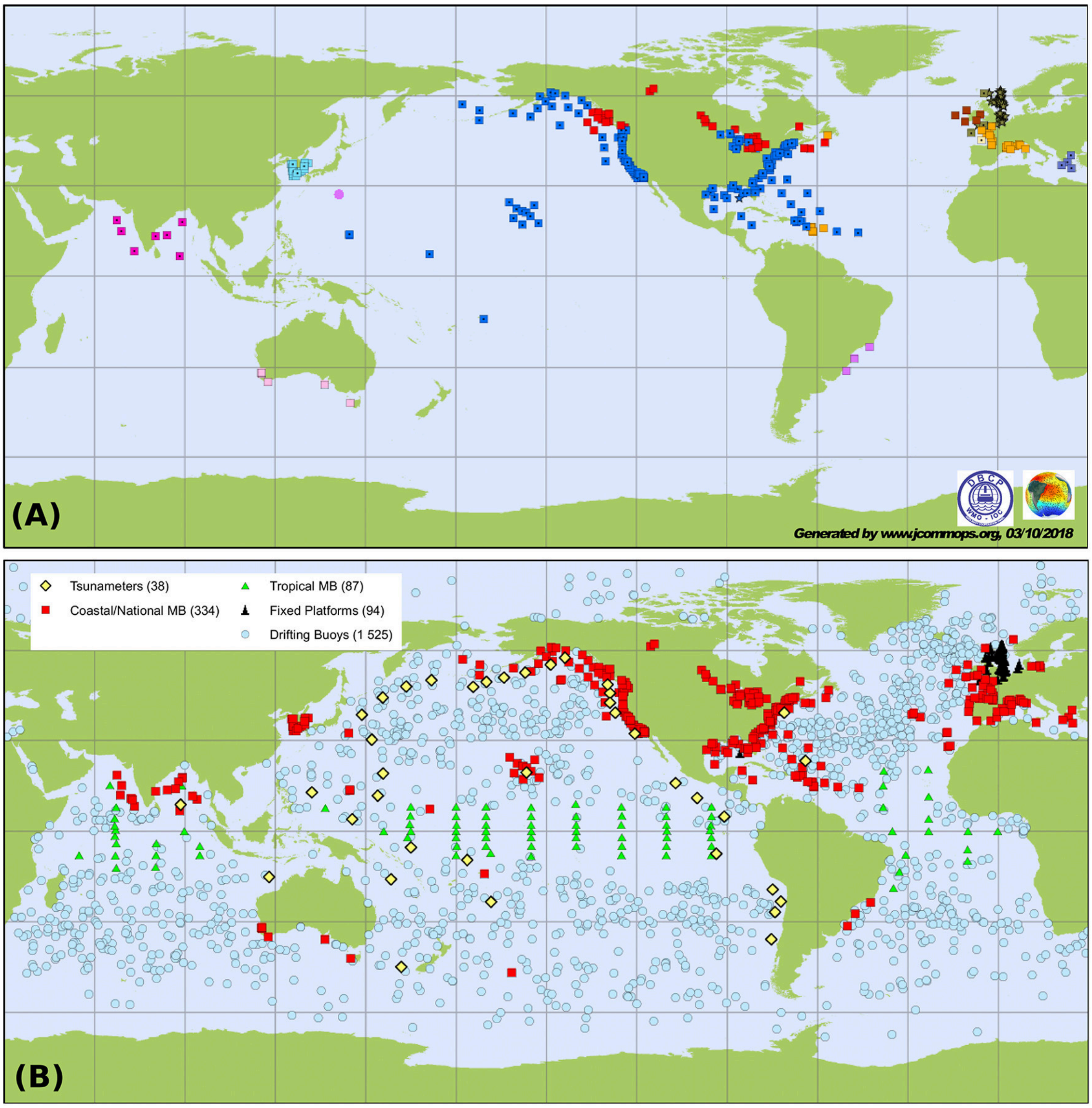

FIGURE 13 | (A) Fixed locations for wave data transmitted via JCOMM, with different colors for different countries, and **(B)** location of surface instruments transmitting data through the GTS as part of the Data Buoy Cooperation Panel (DBCP) which could all be equipped with cheap wave sensors, source http://www.jcommops.org/dbcp/network/maps.html.

important for the forcing of wave models or the interpretation of wave measurements (see **Figure 2**).

Among the novelties that was brought by the European Copernicus program are the long term commitment to continue series of SAR imagery with wave mode data, the use of a constellation of two C-band SAR (Sentinel-1 A and B instead of one with respect to previous European mission) and the modification of the wave mode for an improved sampling of swells (two incidence angles instead of one with respect to previous European mission). This means that the extension of the Sentinel-1 mission is already planned and agreed between the European Commission and the European Space Agency with Sentinel-1C and -1D launches planned for 2022 and 2023. They will ensure the continuity of Copernicus service at least until the end of 2030. With Sentinel-1 mission, waves from SAR have also been formally integrated into the Marine Service (CMEMS).

This includes Level-2 and higher level products such as the "Fireworks". Relying on the self-consistency of a given swell field, the swell measurements are analyzed at the ocean basin scale to flag outliers and provide quality-controlled swell fields. Overall, about 50% of the Level-2 swell measurements are filtered. The consistency between these measurements and the unqualified Level-2 swell measurements is verified using cross-overs between neighboring swell observations. Swell measurements propagated up to 48h are co-located (maximum distance <200 km) and their peak direction and peak wavelength compared, thus providing several thousands of co-located points in a single month, over open ocean regions not sampled by *in situ* measurements.

Such high level products also allows one to combine Sentinel-1 A and Sentinel-1 B products providing inter-calibrated swell measurements. In this context, the recent launch of CFOSAT, will provide new directional ocean wave spectra measurements at global scale. "Fireworks" analysis will quickly provide inter-comparisons with Sentinel-1 mission data, leading to a possible inter-calibration step with the goal of using together CFOSAT and Sentinel-1 data to feed the Level-3 and Level-4 Copernicus waves products.

As a matter of fact, in addition of their complexity (2D spectrum of ocean swell + swell partitions to be compared to significant wave height from altimeters), the quality of the SAR spectra is still poorly documented in the Level-2 products and consequently these products are very little used. But the proper calibration (e.g., Li et al., 2018) and the foreseen developments to include a robust quality flag (for each swell partition) in the Level-2 products should foster a wider use of these data that provide a unique view with a great coverage of global swell fields (**Figure 8C**). Also, more efforts on the larger images using Sentinel-1 and other missions is leading to interesting coastal applications (e.g., Rikka et al., 2018). Possible future constellation of SARs may greatly enrich this capability.

In ice-covered waters, high frequency waves that are usually responsible for nonlinear distortion are attenuated quickly (Wadhams et al., 1988). Therefore, wave signatures on SAR imagery in sea ice are mainly due to velocity bunching (Vachon et al., 1993; Ardhuin et al., 2015). Standard techniques, like the quasi-linear approach (Chapron et al., 2001a), are not sufficient to capture the nonlinearity of the wave features on the SAR imagery. By only considering the velocity bunching mechanism, maps of orbital wave motions can be inverted, giving access to the full $E(k, \theta)$ wave spectrum (Ardhuin et al., 2017a). Further development of this wave retrieval, with the handling of ice features (Stopa et al., 2018b), is opening great opportunities for applications, with the systematic analysis and investigation of wave attenuation in ice (Ardhuin et al., 2018; Stopa et al., 2018a; see **Figures 14A–F**).

Finally, CFOSAT is producing its first wave spectra down to 70 m wavelength (typically a period of 6.7 s), this is a clear demonstration of the power of real aperture radars, in Ku-band in the case of SWIM on CFOSAT, for monitoring waves in the open ocean. Using a Ka-band radar instead makes it possible to resolve shorter components, probably 20 m (3.6 s), with smaller footprints and a wider swath. This is one of the goals of the Surface KInematics Multiscale (SKIM) mission (Ardhuin et al., 2018), which is designed to measure both currents and wave spectra, and is presently undergoing a detailed study for a possible launch in 2025.

Other imaging methods, using constellations of radar or optical sensors will probably further expand our capabilities to monitor sea state. Optical imagery is unique in providing unambiguous information about whitecaps and their distributions, which are important for applications ranging from navigation safety to upper ocean mixing, surface drift (Rascle and Ardhuin, 2009), and air-sea fluxes.

The future of sea state monitoring is also in its past. Considering both the new and historical data, important evolution in processing algorithms are expected. In particular, for altimeters, alternative retracking solutions have emerged to improve the data quality and quantity for satellite altimetry at the coast (Cipollini et al., 2017). One of the most successful techniques consists of selecting only a portion of the waveform, in order to avoid spurious contamination by the trailing edge (Deng and Featherstone, 2005). While the main focus was on the range retrieval, some of these studies have included specific performance analysis for H_s (Passaro et al., 2015; Roscher et al., 2017, 2018; Dinardo et al., 2018). The use of different fitting methods can also lead to a much lower noise in H_s estimates (Ardhuin et al., 2017b). All of these new methods can be combined with adaptive filters to separate tracker noise from geophysical signals (Quilfen et al., 2018), as illustrated in **Figure 2**.

5. RECOMMENDATIONS

We list here a few practical things that could make future sea state observation more useful and valuable.

5.1. *In situ* Observational Systems

There is a clear requirement for more high-quality directional wave spectral data in all parts of the global ocean. With the development of new low cost sensors and cheaper platforms, transition of non-directional wave measurement sites to directional capability should be pursued.

With the continued development of new wave measurement systems, as well as for the historical measurements that make up the climate record, test and evaluation remains critical to the understanding of the differences found, as originally stated in Swail et al. (2009). Testing should consider spatially differing wave climates, and temporally span multiple years (inter-annual variability). The evaluation procedure should include integral wave parameters, frequency, frequency-directional estimates, hierarchy evaluation techniques, and to establish a set of standardized metrics defining the quality of the wave measurement system.

A global network of directional spectral wave drifters, supplemented as feasible by targeted campaigns such as deploying wave drifters in advance of large storms including hurricanes, should be implemented over the next decade. This network may include new platforms, including ships of opportunity (Nielsen et al., 2019), once their errors are known. Adding many doubtful data should not be thought as a replacement for high quality measurements that are particularly needed for long term climate monitoring and statistics on extreme events.

5.2. Historical Data and Metadata

As equally important to high-quality directional wave measurements, self-describing metadata is necessary to define

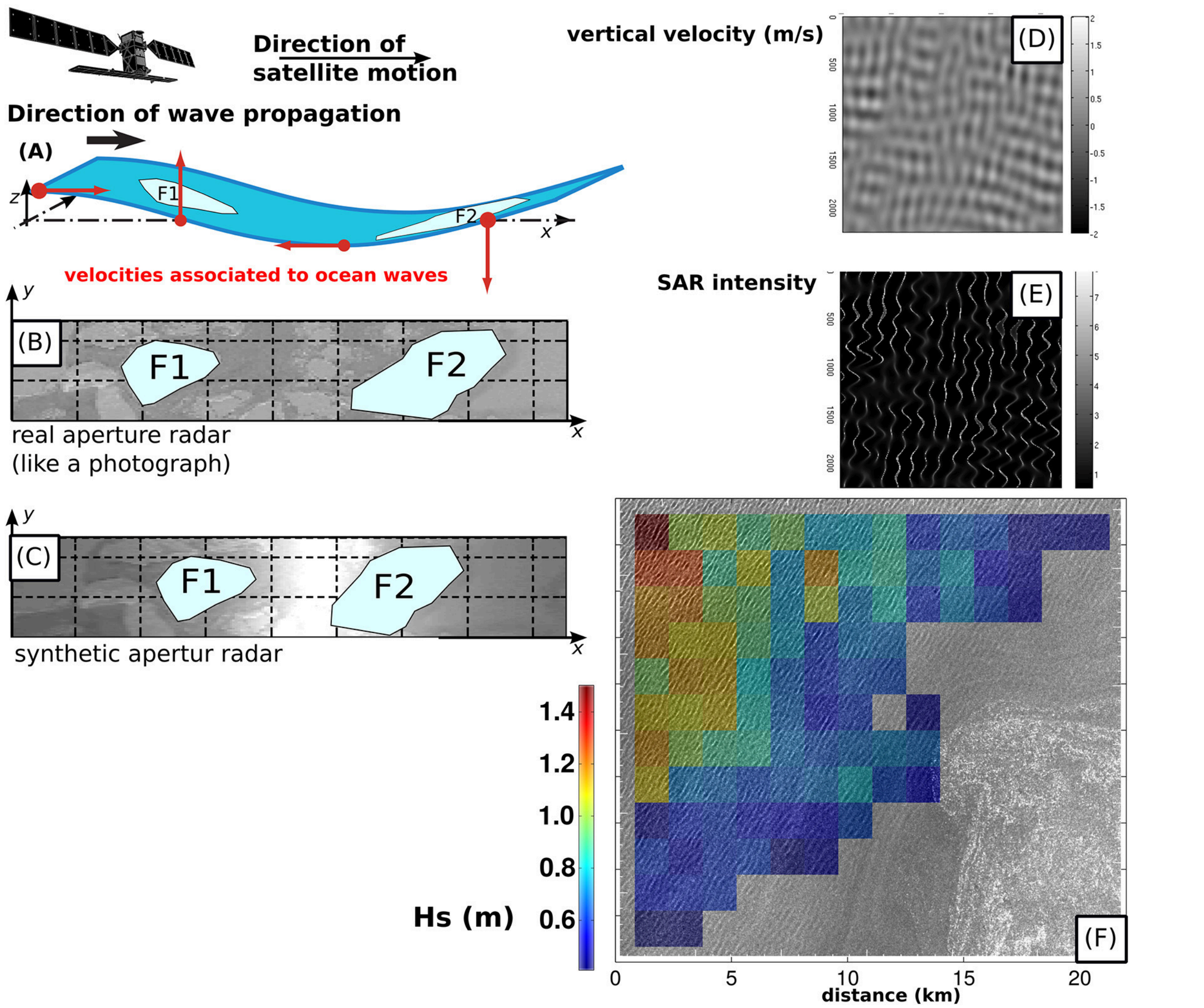

FIGURE 14 | (A) schematic illustrating the geometry of SAR observation and vertical velocities at the surface. **(B)** Example of a real aperture radar scene stretched into **(C)** a SAR scene due to varying vertical velocities in the azimuth direction: actual features such as ice floes *F*1 and *F*2 appear displaced in the azimuth (x) direction. **(D)** example of simulated vertical velocity map due to two swell trains propagating at right angles and **(E)** simulated SAR intensity in the case of a sea surface with uniform σ^0. **(F)** Intensity map (gray shades) observed by Sentinel-1A in Southern Ocean sea ice on 03/05/2016 at 10:55:53 UTC, and overlaid map of H_S in color obtained by inverting the SAR intensity pattern into a vertical velocity map. This example is further discussed in Stopa et al. (2018b).

all characteristics associated with the data. The world's wave measurement data providers are addressing this issue with existing information. However, large gaps still exist in the metadata records from historical deployments. Without this valuable information, there will be a continuation of misrepresenting long-term wave measurement records as identified by Gemmrich et al. (2011). In addition, the metadata records for all *in-situ* wave measurements need to be archived and made easily accesible to any user requiring the information. Ideally, these wave metadata would be archived with the actual measured data in a centralized Global Data Assembly Center (GDAC). GDACs have been created for other data sets (e.g., Pinardi et al., 2019), but not as yet for waves.

5.3. Data Sharing and Distribution

To serve the full range of users, any *in situ* wave observation network should accurately resolve the details of the directional spectral wave field as well as providing the standard integrated parameters. It is strongly recommended that all directional wave measuring devices should reliably estimate the "First 5" standard parameters, and that these spectral parameters be distributed in an easy-to-use format, possibly following the example set by the Coastal Data Information Program (CDIP). We appreciate the sharing of long time series such as the 39-year Aqua Alta data (Pomaro et al., 2018). However, we are missing a common repository or portal for accessing multiple data sets from multiple sites.

5.4. Open Processing, Re-processing, and Algorithms

Given the complexity of all the steps necessary to get from the raw data to a final product, we recommend that algorithms and associated ancillary data be fully documented and published, at least in technical reports. This particulary include any calibration (e.g., for the power in altimeter waveforms).

In the case of remote sensing data (true for altimeter and SAR), the number of available sensors, the co-existence of different algorithms and alternative processing methods invite to produce homogeneous (format) and (inter-calibrated) data sets covering the whole period since the beginning of the earth observation area. New sensors such as CFOSAT for wave spectra, concept missions like SKIM or recent SAR altimeters, all with new and specific capabilities, also advocate for a strategy to build a common and tractable database that will ease the use of the remote sensing data for science applications by non-experts.

5.5. Leveraging Acquisition Capability of SARs

The acquisition capabilities of satellites is under-used today for the monitoring of extreme events. For example, high winds can now be estimated from Sentinel-1 satellites when acquired in cross-polarization (Mouche et al., 2017). A systematic acquisition over severe storms, and a similar measurement of waves in ice (Ardhuin et al., 2017c) could provide critical information on sea states and associated parameters in situations of practical use as well as high value for research.

5.6. Combining Data and Models

Wave assimilation methods have been developed in many fields, but has long been limited in the case of ocean waves due to the fact buoys were close to the coast, hence having a impact on a very short time, or that altimeters only measured wave heights with a limited improvement on spectra, and in particular swells in long-range forecasts. Now that more drifting buoys are becoming available, and that new satellites are measuring more of the spectrum, there is room to fully exploit the space-time correlation structures of swells (e.g., Delpey, 2012) as provided by models and data, both for the optimization of initial conditions and the estimate of model parameters. We note the recent work by Crosby et al. (2017) who optimized the offshore directional wave spectrum at the boundary of a coastal wave model, and similar work could be developed to optimize the wind, current and sea ice parameters that are part of the forcing functions of wave models.

6. SUMMARY AND CONCLUSIONS

The past decade has lead to an amazing increase in the quantity and quality of sea state data collected and distributed, in particular from satellites and in seismic records. These new data are revealing new features of the oceanic wave field, and in particular the importance of ocean currents in defining the small scale variability. As a result, new observation systems should take into account this variability, which is why we propose a new set of requirements for sea state monitoring (**Table 1**). In the short term, reaching these requirements will require a proper combination of *in situ* and satellite data with numerical wave models. Besides, this also requires a better knowledge of winds, currents, and sea ice properties, to which new remote sensing efforts such as SKIM (Ardhuin et al., 2018) can contribute, but which can also benefit from a more creative use of existing data (e.g., Quilfen et al., 2018; Rio and Santoleri, 2018).

At the same time, the *in situ* observation networks have matured and gone through important changes in terms of sensors use and data distribution, with, unfortunately, the metadata often lagging behind. Now that human activities are being more and more exposed to marine hazards due to sea level rise, coastal land subsidence, and intensification of extreme storms, a careful work of documenting and understanding wave climate and its variability is required. This is calling for continued support and funding for basic data collection and quality control, including the archival of metadata, and new research on analysis methods combining all sources of data variability, in particular for the extreme events. Given the relatively short record of buoy and satellite data, other sources of information have probably an important role to play. These include visual observations from ships and seismic records, but the methods to combine all these data and reduce the uncertainties on trends to acceptable levels have yet to be refined, tested and validated.

AUTHOR CONTRIBUTIONS

GQ and MP contributed the initial version of sections on satellite altimeters, JS and IY wrote the sections on trends, JJ, VS, and FA wrote the section on requirements, RJ and VS contributed the initial versions of sections on *in situ* data, AM, JS, and FA wrote the sections on the other sensors (SARs, CFOSAT, SKIM, seismometers). All authors contributed to the final editing.

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METHODS
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Concept Design of the "Guanlan" Science Mission: China's Novel Contribution to Space Oceanography

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Among the various challenges that spaceborne radar observations of the ocean face, the following two issues are probably of a higher priority: inadequate dynamic resolution, and ineffective vertical penetration. It is therefore the vision of the National Laboratory for Marine Science and Technology of China that two highly anticipated breakthroughs in the coming decade are likely to be associated with radar interferometry and ocean lidar (OL) technology, which are expected to make a substantial contribution to a submesoscale-resolving and depth-resolving observation of the ocean. As an expanded follow-up of SWOT and an oceanic counterpart of CALIPSO, the planned "Guanlan" science mission comprises a dual-frequency (Ku and Ka) interferometric altimetry (IA), and a near-nadir pointing OL. Such an unprecedented combination of sensor systems has at least three prominent advantages. (i) The dual-frequency IA ensures a wider swath and a shorter repeat cycle which leads to a significantly improved temporal and spatial resolution up to days and kilometers. (ii) The first spaceborne active OL ensures a deeper penetration depth and an all-time detection which leads to a layered characterization of the optical properties of the subsurface ocean, while also serving as a near-nadir altimeter measuring vertical velocities associated with the divergence, and convergence of geostrophic eddy motions in the mixed layer. (iii) The simultaneous functioning of the IA/OL system allows for an enhanced correction of the contamination effects of the atmosphere and the air-sea interface, which in turn considerably reduces the error budgets of the two sensors. As a result, the integrated IA/OL payload is expected to resolve the ocean variability at submeso and sub-week scales with a centimeter-level accuracy, while also partially revealing marine life systems and ecosystems with a 10-m vertical interval in the euphotic layer, moving a significant step forward toward a "transparent ocean" down to the vicinity of the thermocline, both dynamically and bio-optically.

Keywords: concept design, Guanlan science mission, interferometric altimetry, ocean lidar, space oceanography

INTRODUCTION

Since the advent of ocean radar satellite in the 1970s (Fu et al., 2010), its development has followed three generic trends: (i) better sampling, (ii) higher accuracy, and (iii) more variables. Better sampling of the ocean normally refers to a broader coverage, a deeper penetration, a higher spatiotemporal resolution, and a longer time series. Upgraded sensors with refined algorithms (both theoretical and empirical) are major approaches aimed at improving the accuracy of remotely sensed parameters. Meanwhile, tremendous efforts have been devoted to testing new instrument (e.g., ocean lidar) and deriving new variables from spaceborne measurements. Ideally, the ultimate goal of ocean remote sensing is toward a quantitative derivation of all required variables, with a satisfactory accuracy, and a perfect sampling in near-real time. In reality, however, this can never be fully realized, but can always be gradually approached. In this white paper, the concept design of the Chinese Guanlan science mission with an interferometric altimeter (IA) and an ocean lidar (OL) onboard is described. We will demonstrate that the IA payload is expected to make a significant contribution to satellite altimetry in aspects of the above-mentioned trends (i) and (ii), while the OL payload is a good example of expanding remote sensing capacity in aspects of those trends mentioned in (i) and (iii).

Satellite Altimetry

The history of satellite altimetry can be largely divided into three phases as summarized in **Table 1**. (i) Phase I (1970–1980s): the mesoscale "diamond" phase; (ii) Phase II (1990–2010s): the semimesoscale "grid" phase; (iii) Phase III (2020s onward): the submesoscale "pixel" phase. Here we use three keywords to characterize the major geographical pattern of altimeter data products for each phase, which corresponds to an overall spatial resolution of ∼100 km, ∼50 km, and ∼10 km, respectively. In Phase I, traditional altimeters in exact-repeat orbits measure sea surface height (SSH) along intersecting ground tracks every 3/17 days (e.g., Fu, 1983). The regions between tracks (normally ∼1.5° along the equator) form a diamond pattern within which SSH is never sampled. In Phase II, the idea of "virtual constellation" of multiple altimeters operating simultaneously considerably improve the sampling, leading to the construction of a gridded SSH product (mostly 0.25° × 0.25°) on a daily basis (e.g., Ducet et al., 2000; Pujol et al., 2016). In the upcoming Phase III, wide-swath IAs will hopefully "image" the sea surface topography with a "pixel" size of less than 10 km × 10 km every 1–3 days (e.g., Fu and Ferrari, 2013).

The accuracy of sea level measurements has also been steadily improving from >10 cm to <5 cm throughout the past half century and will probably reach the level of ∼1 cm in the next decade. The combination of refined sampling and improved accuracy, as well as increasing time series, has naturally brought about continuous, sometimes critical, progress in dynamic oceanography. In the "diamond" phase, the technological feasibility, and scientific utility of satellite altimetry has been demonstrated by the GEOS-3, Seasat and Geosat missions, from which many interesting yet semi-quantitative results, such as signatures of basin scale ocean gyres, the Antarctic Circumpolar Current, as well as mesoscale ocean variabilities, have been obtained (e.g., Fu, 1983).

In the "grid" phase that followed, the contributions of satellite altimetry to ocean sciences are quantitative and substantial, while some are regarded as fundamental and even revolutionary. Typical examples include the systematic observation and a better understanding of ocean circulation, the Rossby wave, and the mesoscale eddy. First, altimetrically determined ocean topography has provided the first test bed for examining the performance of global ocean general circulation models at large scales (∼5 cm rms for wavelengths longer than 1000 km), although its further improvement requires more accurate geoid knowledge over a wide range of scales (Fu and Chelton, 2001). Second, altimetric measurements of SSH reveal a persistent westward propagation with characteristics similar to the linear Rossby waves by which the ocean adjusts to wind and thermal forcing (Chelton and Schlax, 1996), though it is now evident that the variability due to Rossby waves are only significant at wavelengths of ∼1000 km and longer (Scott et al., 2010). Third, most of the extratropical variability at wavelengths of ∼100−500 km, previously thought to be linear baroclinic Rossby waves, is actually westward propagating non-linear eddies that are nearly ubiquitous in the world oceans (Chelton et al., 2011b).

As the first planned mission of its kind in the upcoming "pixel" phase, the surface water and ocean topography (SWOT) satellite aims to measure both the land water and ocean topography with an unprecedented horizontal resolution (Fu and Ubelmann, 2014). The SWOT satellite will carry a Ka-band radar interferometer, designed to yield high spatial resolutions over two swaths of 50 km, with a 20-km gap centered at the nadir track (Durand et al., 2010). The primary oceanographic objective of SWOT is to characterize the ocean mesoscale and submesoscale circulation at spatial resolutions of ∼10 km and larger. It will also contribute to estimating the vertical motion of the ocean, taking place at scales of 10–100 km, which is important to the understanding of the energy balance of ocean circulation (Capet et al., 2008).

The progress of altimeter based dynamic oceanography has actually been accompanied by debates and controversies. Many of the problems arise due to imperfect (sometimes poor) sampling and inappropriate SSH reconstruction. Much of the hope to tackle these challenges lies in the launch of the next generation IAs, including the upcoming SWOT satellite, and the one that will be flown on our proposed Guanlan mission, which will advance sea level observation from the "grid" phase to the "pixel" phase, and the altimetric oceanography from a mesoscale period to a submesoscale era, when the corresponding levels of dynamic variability in the ocean energy cascade can be effectively resolved.

Spaceborne Lidar

As a pioneer of spaceborne lidar, the US space agency NASA (National Aeronautics and Space Administration) initiated the Lidar In-Space Technology Experiment (LITE) in 1988 (Winker et al., 1996). Following a successful feasibility study with an aerosol and cloud lidar onboard the Space Shuttle of Discovery in 1994, NASA and the French space agency CNES (Centre

TABLE 1 | Three phases of development for satellite altimetry.

Phase	I (diamond) (1970–1980s)	II (grid) (1990–2010s)	III (pixel) (2020s-beyond)
Satellite	GEOS-3, Seasat-A, Geosat	ERS-1,2, TOPEX/Poseidon, Jason-1,2, Envisat, GFO, CryoSat-2, HY-2A, AltiKa, Sentinel-3A	Jason-3, Sentinel-3B, GFO-2, HY-2B, SWOT, Guanlan
Spatial resolution	∼10 km × ∼100 km	<1 km × ∼100 km; 0.25° × 0.25°	<1 km × ∼100 km; <∼10 km × ∼10 km
Temporal resolution (day)	>10	∼10; ∼5	∼10; ∼1
Accuracy (cm)	>10	∼5	∼1

National d'Etudes Spatiales) launched their joint mission of CALIPSO (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation) in 2006 (Winker et al., 2010), which transformed the satellite lidar technology from experimental to operational. In the years that followed, a dozen spaceborne lidars have been proposed by several national and international space agencies such as NASA and ESA (European Space Agency).

As a key element of the Aqua constellation (A-train), CALIPSO has three co-aligned major instruments (Winker et al., 2009): A 3-channel lidar (the Cloud-Aerosol Lidar with Orthogonal Polarization, CALIOP), an imaging infrared radiometer, and a wide-field camera. The primary goals of the CALIPSO mission include: (i) Observationally based estimates of direct and indirect aerosol radiative forcing; (ii) Improved characterization of surface longwave radiative fluxes and atmospheric heating rates; (iii) Improved model parameterizations of cloud-climate feedbacks. In short, the main purpose of CALIPSO is to provide a long-term mapping of the horizontal and vertical distributions of aerosol and cloud properties over the entire globe.

Despite of its atmosphere-climate oriented nature, the CALIPSO mission has provided valuable by-products for oceanographic studies throughout the past decade (see Hostetler et al. (2018) for a recent review). Behrenfeld et al. (2013) used CALIOP measurements to quantify global ocean phytoplankton biomass and total particulate organic carbon stocks. Lu et al. (2014) found significant relationships between integrated subsurface backscatter and chlorophyll-a concentration, as well as particulate organic carbon, which indicate a potential use of the CALIPSO lidar to estimate global chlorophyll-a and particulate organic carbon concentrations. Lu et al. (2016) introduced an approach to estimate the ocean subsurface layer-integrated backscatter and particulate backscattering coefficient from CALIOP 30° off-nadir lidar measurements. Behrenfeld et al. (2017) reported a decade of uninterrupted polar phytoplankton biomass cycles, and found that polar phytoplankton dynamics are categorized by "boom–bust" cycles resulting from slight imbalances in plankton predator–prey equilibria.

Compared to historical passive optical remote sensing of the ocean, spaceborne lidars have at least two unique advantages: First, vertical penetration into the mixed layer through which profiles of optical and even oceanographic properties can be quantitatively obtained; Second, an all-time measurement independent of solar radiation can be carried out. But the critical limitation, that all measurements are vertically integrated without depth information, remains. A dedicated spaceborne lidar such as the one proposed for the Guanlan science mission is therefore urgently needed in order to better understand the truly three-dimensional (3-D, rather than 2.5-D) structures in the subsurface ocean.

Scientific Goals

The primary scientific goals of the Guanlan mission are defined as follows:

(i) To resolve sea level variability at submeso and sub-week spatiotemporal scales with a centimeter accuracy using the IA instrument, so that global oceanic eddies (especially those short-lived small ones missed by current altimeter constellations) can be tracked individually during their full lifetimes.

The dominant scales of oceanic eddies range from days to years in time and from tens to hundreds of kilometers in space, serving as a key bridge of an energy cascade between large and small variabilities in the ocean. As evidenced in the SSH snapshot of the northwest Pacific derived from AVISO data (AVISO, 2016), both cyclonic and anticyclonic eddies are ubiquitous in the ocean and cover a variety of spatial scales (**Figure 1a**). Big eddies are obviously associated with strong currents along the mainstream and extension areas of the Kuroshio. Looking into an individual oceanic eddy, we further disclose the complexity of its inner structure (**Figure 1b**): A ∼10 km sized eddy "eye" with a minimum speed in the core region, surrounded by an internal circulation with an outward increasing geostrophic velocity until a maximum value is reached near the eddy boundary. In terms of lifetime evolution, eddies often fall into the submesoscale in size at birth and death (they usually last for 1 or 2 weeks), while remaining relatively energetic in the mesoscale for the rest of the time (Chen and Han, 2019). Therefore, a spaceborne IA with a submesoscale and a sub-week resolving capability is necessary for the full life cycle of an oceanic eddy to be continuously tracked.

(ii) To penetrate effectively into the oceanic mixed layer with the active OL instrument, so that a vertical derivation of the optical properties of the subsurface ocean can be obtained which may lead to an improved characterization of the thermocline formation and its associated dynamic features (**Figure 2a**).

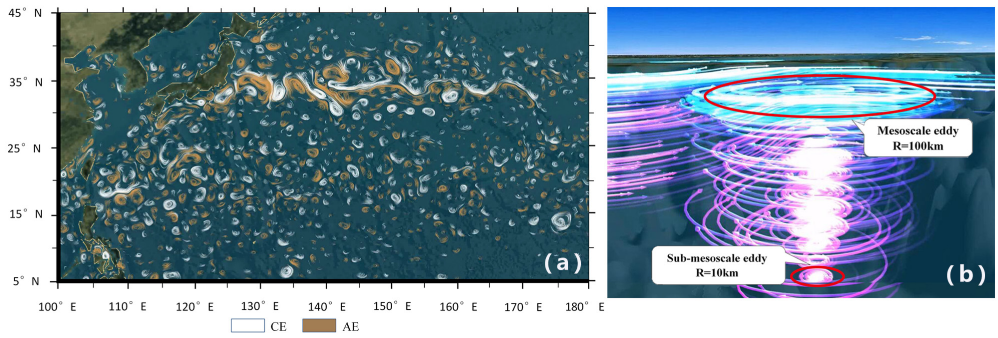

FIGURE 1 | (a) A snapshot of massive eddies in the Northwest Pacific Ocean. **(b)** A typical example of the three-dimensional structure of an individual oceanic eddy.

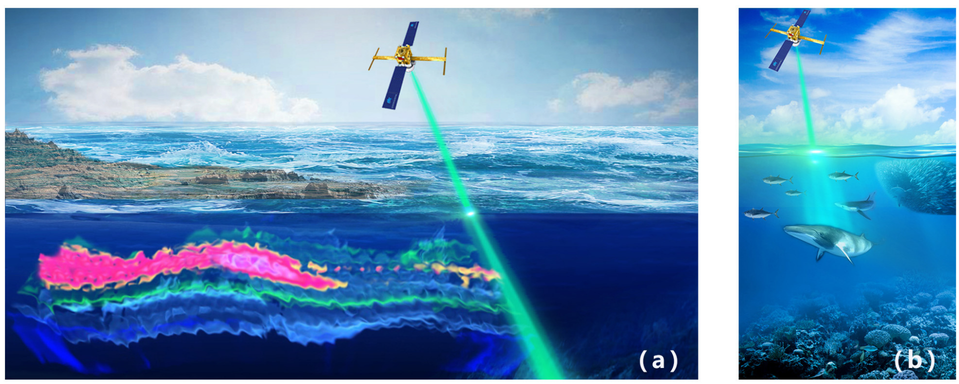

FIGURE 2 | (a) Schematic of thermocline profiled by a spaceborne ocean lidar. **(b)** Schematic of fish school detected by a spaceborne ocean lidar.

Efforts to understand and model the dynamics of the upper ocean will be significantly advanced once the capacity to rapidly determine mixed layer depths (MLDs) over large regions is built. Spaceborne lidar technology is a potential choice for achieving this goal, since it has been demonstrated that the MLDs can be effectively derived from ocean optical properties (Zawada et al., 2005). The idea of this approach is based on the fact that optical properties are, to a large extent, determined by the biological productivity in the ocean which is proportional to the MLD (e.g., Behrenfeld and Falkowski, 1997). In other words, the frequent association of plankton layers with the pycnocline (Dekshenieks et al., 2001) implies that the pycnocline depth can often be mapped by a lidar system (Churnside and Donaghay, 2009; Churnside et al., 2013). In a feasibility study, Zawada et al. (2005) observed that the optical properties are strongly influenced by suspended particle concentrations, which generally reach a maximum at pycnoclines below the MLD. Quantitatively, a 70% agreement is found between the best hydrographical-optical algorithm pairings. This correlation is expected to be further increased when the active lidar system is used to complement the conventional passive optical remote sensing, as a result of the improvement from vertical integration to depth distribution. **Figure 3** shows the estimated optical MLD with respect to the hydrological MLD as a function of latitude (partially adapted from Chen and Yu, 2015), which suggests that passive optical remote sensing can largely reach the thermocline depth in the tropical ocean, while a 100–200 m gap will rely on active lidar technology to fill in.

(iii) To detect direct signals from big ocean fish and animals, and indirect signatures from various species of phytoplankton and zooplankton in the euphotic layer by OL in order to partially reveal the preliminary characteristics of the marine food web and the corresponding ecosystem.

As understood, lidars can produce depth-resolving profiles of various constituents of the ocean. The feasibility of detecting fish schools with an airborne lidar was demonstrated by Murphree et al. (1974), and has been confirmed by several subsequent analyses (e.g., Churnside, 2014). An ideal case is when large fish gather "separately," so individuals can be "seen" and even be counted in the return signals (**Figure 2b**). A successful example is the depth and position of sixty-nine individual fish that are reported using the cross-polarized lidar signal at night, off the Oregon coast, most of which are suspected to be albacore tuna (Churnside et al., 2009). In addition to the measurements of phytoplankton and zooplankton, it is now clear that ship- or air-borne lidar can be used not only to estimate the biomass for

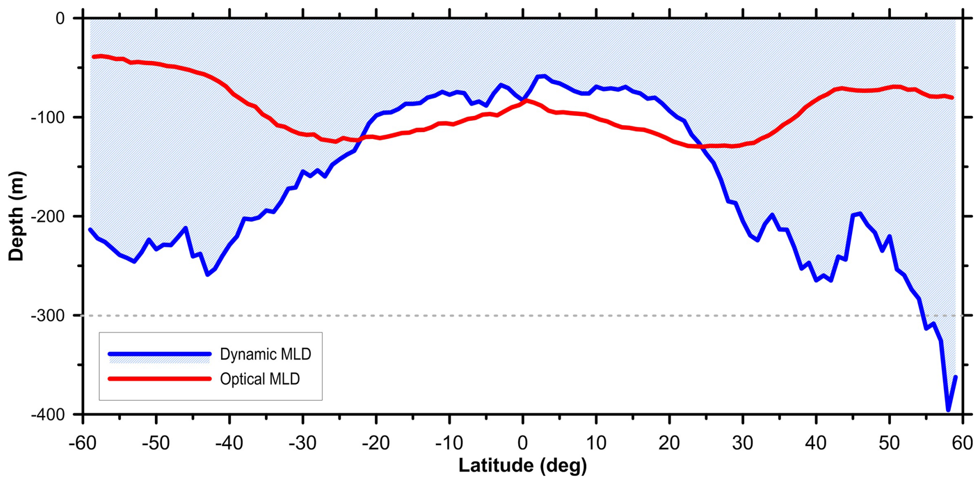

FIGURE 3 | Zonally averaged MLD for the global oceans. The red and blue lines correspond to the optically and hydrographically derived MLDs, respectively.

fisheries, but also to investigate aspects of fish behaviors. Based on the experience gained with CALIOP, it seems feasible to build a spaceborne lidar with a depth resolution of ~10 m to better match the oceanographic requirements. Combined with ocean color measurements, the OL would be a powerful tool for global observations of the upper ocean food web and marine ecosystem (Stephens et al., 2010).

SATELLITE CONFIGURATION AND PRIMARY PAYLOADS

Among the various challenges in satellite observation of the ocean that need to be tackled, the following two issues are probably of a higher priority: inadequate dynamic resolution (i.e., kinetic energy leakage), and ineffective vertical penetration (i.e., ocean interior opaqueness). It is therefore the vision of the National Laboratory for Marine Science and Technology of China in Qingdao (QNLM) that two highly anticipated breakthroughs in the coming decade are likely to be associated with radar interferometry and lidar profiling technology, which would make a substantial contribution to an eddy-resolving and depth-resolving observation of the ocean. As an expanded follow-up of SWOT and an oceanic counterpart of CALIPSO, the planned Guanlan science mission comprises a dual-frequency (Ku and Ka) IA and a near-nadir pointing OL, as illustrated in **Figure 4**.

The Interferometric Altimeter Instrument

The Guanlan IA takes the two-side observation geometry with multiple Ku and Ka band interferometric beams at a relatively large range of incidence angle (**Figure 5**) so as to achieve a wider swath compared with SWOT. As shown in **Figure 6**, the Guanlan IA system is composed of pairs of multi-beam antennas, Ku/Ka front-ends, Ku/Ka SSPAs (solid state power amplifier), and multi-channel Ku/Ka receivers, as well as a Ku/Ka transmitter, a frequency synthesizer, central control electronics, and an onboard data preprocessing unit. Design considerations for each unit are briefly explained below.

The Ku/Ka multi-beam antenna takes the form of a slotted-waveguide array, and the two antennas are identical, each with five beams, with two beams looking left (Ku/Ka), two beams looking right (Ku/Ka), and one beam looking nadir (Ka). The slotted waveguide array antenna can have a very stable phase center, which has been proven by the Tiangong-2 IA currently in orbit. Unlike a synthetic aperture radar (SAR) or an interferometric SAR, a smaller azimuth-size antenna instead of a large one is preferred for our IA. The initial design indicates that the antenna can be less than 3 m long.

The Ku/Ka front-end routines transmit Ku/Ka signals to different beams of the antenna and forward the received Ku/Ka echo signals to the Ku/Ka receivers, where an inner-calibration loop is incorporated by which the transmitted power and the phase can be monitored accurately and periodically. Special consideration should be given in order to handle the obvious challenge of high power.

Based on the successful application of a Ku-band high power SSPA, we are confident that it will have a stable performance, i.e., phase stability of the transmitted signal and long-lifetime, good electromagnetic compatibility and safe operation (anti-micro-discharging in space environment). The required maximum transmitted powers of both Ku and Ka SSPAs exceed 1000 W. Comprehensive measures should be taken for the thermal control due to the relatively low power efficiency compared to the traveling wave tube amplifier (TWTA). Since a power combination technique is used to achieve high energy transmission, it is easier to realize the power-control given that the transmitted power can be scaled according to different orbit heights.

Ku/Ka multi-channel receivers are also very crucial for obtaining a stable and accurate interferometric phase measurement, which is almost the only un-calibratable factor dominating the random height error budget. The design should consider issues both at device level [e.g., low noise amplifier,

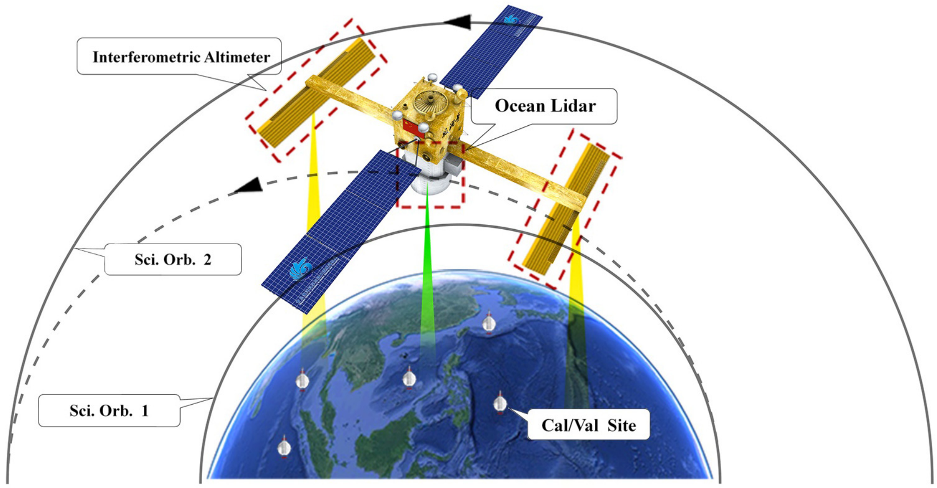

FIGURE 4 | The orbit configuration and payload system of the Guanlan mission.

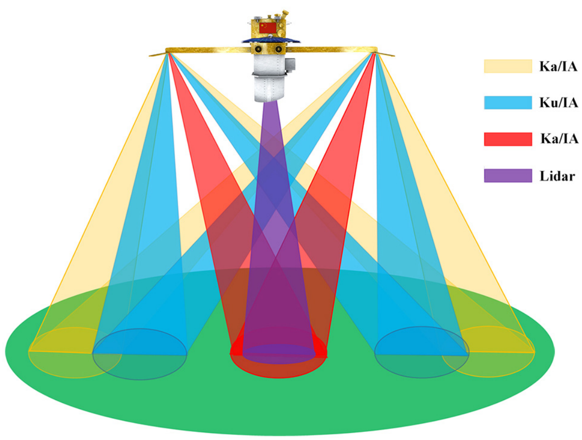

FIGURE 5 | Measurement scheme of the Guanlan IA/OL system.

mixers, filters, radio frequency (RF), intermediate frequency (IF) and video amplifiers, in-phase, and quadrature demodulators] and at a circuit level (the layout and the isolation between RF and LO (local oscillator) frequency, and between LO and IF), as well as those related to the working environment, so as to guarantee the phase stability of the received signal from input to output. Our goal is to make the stability of the interferometric phase measurement better than 0.1° on a single pulse basis.

The frequency synthesizer unit uses a low phase noise and high stability atomic clock. The required LO frequencies for the transmitters/receivers, the working clock, the data sampling clock, and the data transmission clock, used by the central control electronics, are all generated directly from it or by phase referring to it. The low phase noise and low spurious performance of each frequency is very important for the phase stability of the interferometric system. The system architecture determines that the LO frequencies should be generated locally, i.e., the frequency synthesizer should be designed in a distributed fashion.

The central control electronics & onboard data preprocessing unit is responsible for controlling the entire working process according to different operating modes. Being adaptive to an orbit height variation from ∼500 to ∼800 km, the controlling time sequences for signal transmitting/receiving and data recording play a key role in realizing highly accurate and coherent measurements. The multi-channel analog to digital convertors (ADCs) should be highly synchronized at a picoseconds level. This unit is also in charge of all kinds of communications between the satellite and the payloads via various buses, as well as the transmission of science data to the ground station. Onboard data preprocessing is necessary in order to reduce the transmission rate under continuous observations.

The Guanlan dual-frequency IA takes the complementary advantages of the atmospherically less influenced Ku-band and the ionospherically insensitive Ka-band signals with a large B/λ value (B is the baseline length and λ is the wavelength), which facilitates accurate height retrieval under a wide swath over the ocean (**Figure 5**). The Ku band is designed to cover an inclining angle from 1° to 5.5° while the Ka band from 4.5° to 6°, forming an overlapped region between 4.5° and 5.5°. It should be pointed out, however, the large range between the two orbit heights corresponding to the two operational modes (∼500 km vs. ∼800 km, as will be addressed in the following section) could be a challenge for the design of the Guanlan IA.

It should be emphasized that B is a critical parameter for the IA, and there is an intrinsic conflict between its length and the system complexity: a longer baseline is good for achieving higher sensitivity of phase to height, but a more complicated in-orbit measurement system is required, and the interferometric phase may suffer from more serious motion errors and spatial decorrelation. A compromised B value has to be found along with

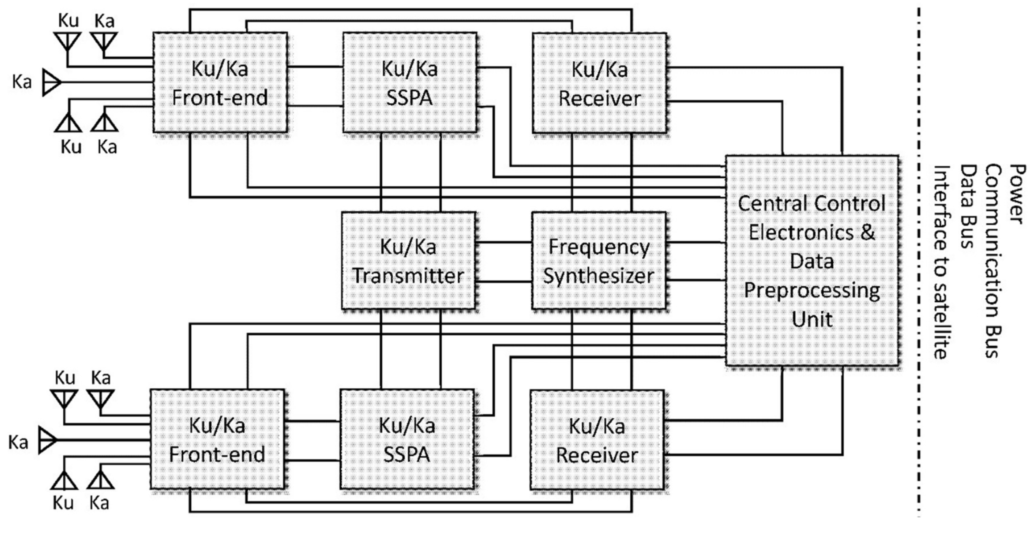

FIGURE 6 | Component diagram of the Guanlan interferometric altimeter.

an optimized orbit. Initial simulation shows that B should be at least greater than 10 m for our purpose.

The dual-frequency design is helpful to estimate baseline parameters (length and inclining angle). By utilizing the multi-beam antennas, five pairs of interferometry are formed, among which the nadir interferometric beams are useful for polar iceberg observation as well as for monitoring the baseline status over an appropriate (calm) sea surface. Data from the overlapped region can also be used to estimate the ionospheric delay for the Ku band.

The Ocean Lidar Instrument

As an active optical detection instrument capable of providing time-resolving and spectral-resolving measurements, the Guanlan OL is built to perform an all-time profiling of the attenuated coefficients, the backscatter coefficients, and the particle linear depolarization ratios from the sea surface to the mixed layer (**Figure 7**). Additionally, the OL is also designed to make possible measurements of the ocean fluorescence and the sea level elevation. As a complementary device, a multi-channel scanning radiometer may also be carried onboard to optionally conduct high-spectral-resolution passive observations.

The Guanlan OL has two fully redundant lasers, each with a narrow-linewidth laser that transmits simultaneous, co-aligned multi-wavelength (including the blue and green bands) pulses (**Figure 8**). The total output pulse energy is at joule level. The two lasers are expected to cover the full mission lifetime. The primary laser is scheduled to be fired at the launch of Guanlan, while the second one serves as a backup. For the receiver, a Cassegrain telescope with lightweight silicon carbide is designed to collect backscatter signals. The diameter of the telescope is approximately 1.2 m. For accurate measurements of the troposphere and subsurface ocean, a data acquisition subsystem with a high

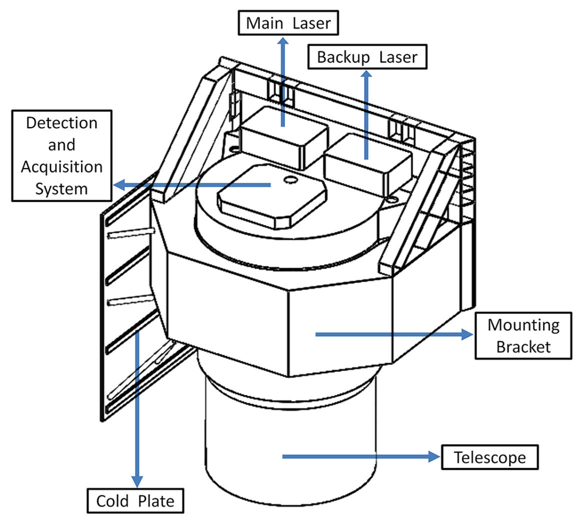

FIGURE 7 | Configuration of the Guanlan ocean lidar.

sensitivity and a large dynamic range is required. Therefore, an analog mode along with a photon counting mode will be operating simultaneously. To ensure data integrity and processing flexibility, high-speed waveform acquisition and variable digital discrimination techniques are adopted. The heat generated by lasers is dissipated via a radiant cooling panel. The OL is installed to the satellite platform in the overall mounting framework.

The technical route of the laser system is a solid-state main oscillation power amplifier combined with a non-linear frequency conversion technology. Multistage laser amplifiers are used to amplify the seed laser pulses from a 1064-nm main oscillator. The frequency of the amplified high energy 1064-nm laser is doubled to obtain 532.2-nm green laser pulses.

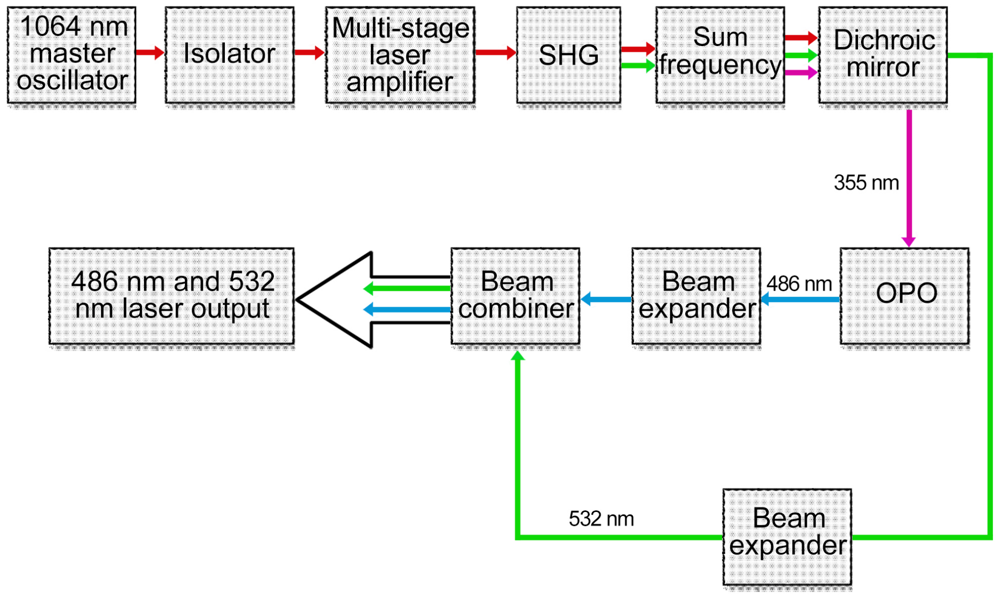

FIGURE 8 | Component diagram of the Guanlan ocean lidar.

A 355 nm ultraviolet laser is generated by a frequency sum of the 532.2-nm laser and the remaining 1064-nm laser. The 486.1-nm blue laser pulses will be generated by the 355-nm laser pumped optical parametric oscillator. Considering the scale and light damage in the actual space environment, multiple lasers are designed to meet with the parameters described above and obtain the 486.1-nm blue laser and the 532.2-nm green laser with single pulse energy greater than 1 joule each. A proper incidence angle will be adopted to avoid ocean surface reflection at nadir.

The receiving telescope adopts a Cassegrain structure, consisting of a primary mirror and a secondary mirror. The mirror-coated metal reflective film has a reflectivity of more than 95% in the blue-green band. The telescope has an effective receiving aperture of 1.2 m and a field of view of 0.2 mrad. Under the premise of ensuring the rigidity and stability of the mirror body, the weight of the telescope is to be reduced as much as possible. The primary and secondary mirrors are made of silicon carbide materials with high rigidity, excellent thermal conductivity, and high stability. The weight of the optimized telescope will be limited to less than 200 kg.

A more sensitive photon counting technique is used to detect laser echoes in multiple channels. With this technology, the echo signal of a single photon can be detected with a count rate of 100 MHz. A good signal-to-noise ratio can be obtained by time integration during the detection. In the case of receiving a large number of photons at the same time, the analog signal output can be realized by the accumulation of multi-channel signals. The analog signal is received by the acquisition card with a sampling rate of 1 GSps, and the continuous signal of the underwater vertical profile can be subsequently collected. The hybrid method of analog sampling and photon counting will improve detection sensitivity meanwhile provide a high dynamic range.

ORBIT/SAMPLING AND CALIBRATION/VALIDATION

Orbit Design and Sampling Strategy

In order to optimize the performance of each payload onboard the Guanlan satellite, two potential science orbits are proposed with a possible mid-term maneuver in between (**Table 2**): A low orbit of 495.953 km which is ideal for the OL to maximize its vertical penetration, and a high orbit of 791.254 km which is necessary for the IA to ensure a wide swath and fine spatiotemporal resolution. For both the low and high orbits, there will be an initial 3-month commissioning phase, followed by a science orbit phase which is expected to last for at least one year each. The orbit inclination of Guanlan is chosen to be 78.0° to cover the polar regions and avoid major tidal aliasings. Other considerations for orbit design include solar radiation, atmospheric contamination, and site selection for calibration and validation (Cal/Val).

A comparison of the sampling density between the Guanlan and SWOT science orbits is shown in **Figure 9**. We tried to simulate the sampling process and estimated the data recovery efficiency under various combinations of Guanlan and SWOT orbits based on a 1/50° SSH grid, which is identical to the spatial resolution of the SWOT simulator. As shown in **Table 3**, the mean revisit times of SWOT, Guanlan science orbit 1 and 2 are 7.87 days, 8.45 days, and 5.61 days, respectively. Combining the Guanlan science orbit 1 or 2 with the SWOT orbit can reduce the revisit time to 4.28 days or 4.01 days, respectively. It is therefore apparent that a wider Guanlan swath (partially

TABLE 2 | Orbit characteristics for Guanlan and SWOT.

Satellite	Guanlan				SWOT	
Orbit type	**Commissioning orbit 1**	**Science orbit 1**	**Commissioning orbit 2**	**Science orbit 2**	**Commissioning orbit**	**Science orbit**
Altitude (km)	536.175	495.953	864.901	791.254	857.244	890.582
Inclination (°)	78.0	78.0	78.0	78.0	77.6	77.6
Exact repeat cycle (days)	0.99288	22.83629	0.99348	13.90869	0.99349	20.86455
Number of orbits per cycle	15	348	14	199	14	292
Ground track equatorial spacing (km)*	2671.669	115.158	2862.503	201.382	2854.254	136.863
Swath width/gap width (km)	112.7/18.7	104.3/17.3	182.0/30.2	166.4/27.6	120.0/20.0	120.0/20.0
IA pixel size (km)	0.5				0.5	

Distance between consecutive satellite orbits.

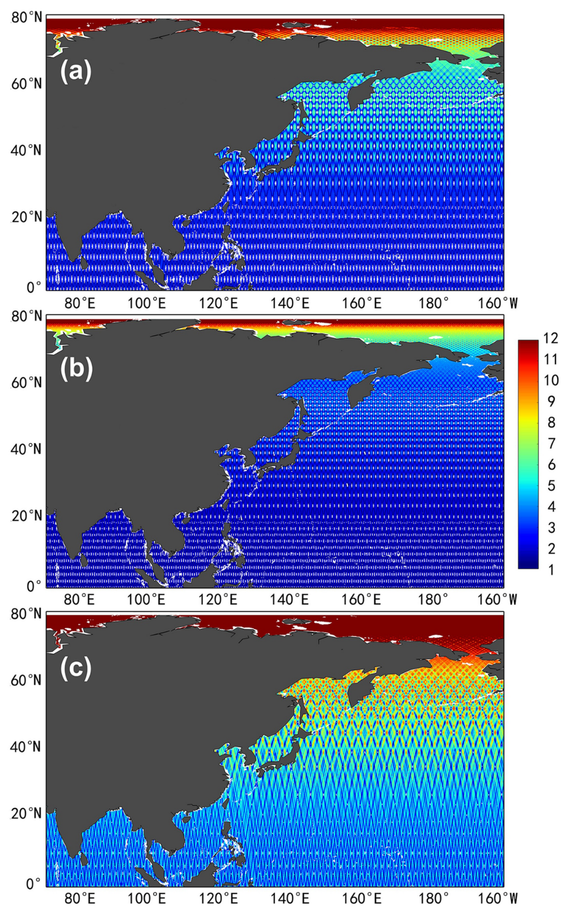

FIGURE 9 | A comparison of the sampling density (within a 1/50° × 1/50° cell) between the Guanlan and SWOT orbits. **(a)** Guanlan science orbit 2. **(b)** SWOT orbit. **(c)** Is a sum of **(a)** and **(b)**.

benefitting from the dual frequency design) or merging of tandem IA measurements can lead to a significant increase of the sampling efficiency by ~1/4–1/2 compared to the SWOT mission alone. It should also be noted, however, that the penetration depth of the OL may have a reduction of 10–15% when the satellite is maneuvered from science orbit 1 to science orbit 2.

The centimeter-level precise orbit determination (POD) of the Guanlan satellite relies on the combination of the Beidou/GPS-based global navigation satellite system (GNSS) and the satellite laser ranging (SLR) system, where the multimode GNSS receiver is used for orbit tracking, the onboard SLR is used for calibrating orbit error, and a multifrequency scheme is applied for eliminating ionospheric errors in the observation data. As the next generation Beidou III system with a global coverage will be established in 2020, the Guanlan mission scheduled beyond that may also have the option to rely solely on the Beidou/SLR system to achieve a centimeter-level POD.

Calibration and Validation Activities

Synchronous calibration/validation of the IA/OL sensors onboard the Guanlan satellite is a challenging task. Calibration of the SSH measurement for a wide swath consists of two stages: ground calibration before launch and in-orbit calibration after launch. In the first stage, the time-delay of each subsystem should be measured on the basis of which the total system delay can be estimated along with the initial phase of each channel and the performance of phase-AGC (automatic gain control). In the second stage, the gain pattern of the antenna, and the absolute phase and time-delay of the whole system will be periodically measured at the Amazon tropical rain forest, and by the arrays of man-made reflectors installed in land and oceanic sites where different kinds of calibration facilities are equipped.

As for the validation of SSH, given the 166.4-km wide swath and the ~5-km pixel size of the Guanlan IA, our primary goal is to effectively resolve the complex dynamic variabilities at ~10–100 km scales induced by the presence of rich submesoscale oceanic motions. No existing observation network can provide a synoptic wavenumber spectrum at these wavelengths. To tackle this difficulty, an integrated multi-sensor validation array is proposed, as illustrated in **Figure 10**. In the selection of validation site, we try to make best use of current observation arrays deployed by the QNLM in the western Pacific-South China Sea-Indian Ocean area, both near the seashore and in the open ocean. Possible collaboration with the SWOT mission will also be considered as far as the IA instrument is concerned. When the satellite overflies the validation platform, accurate SSHs can be derived using joint measurements from GNSS, tide gauges,

TABLE 3 | Mean revisit time for Guanlan and SWOT.

Orbit type	SWOT	Guanlan science orbit 1	Guanlan science orbit 2	Guanlan science orbit 1 + SWOT	Guanlan science orbit 2 + SWOT
Mean revisit time (day)	7.87	8.45	5.61	4.28	4.01

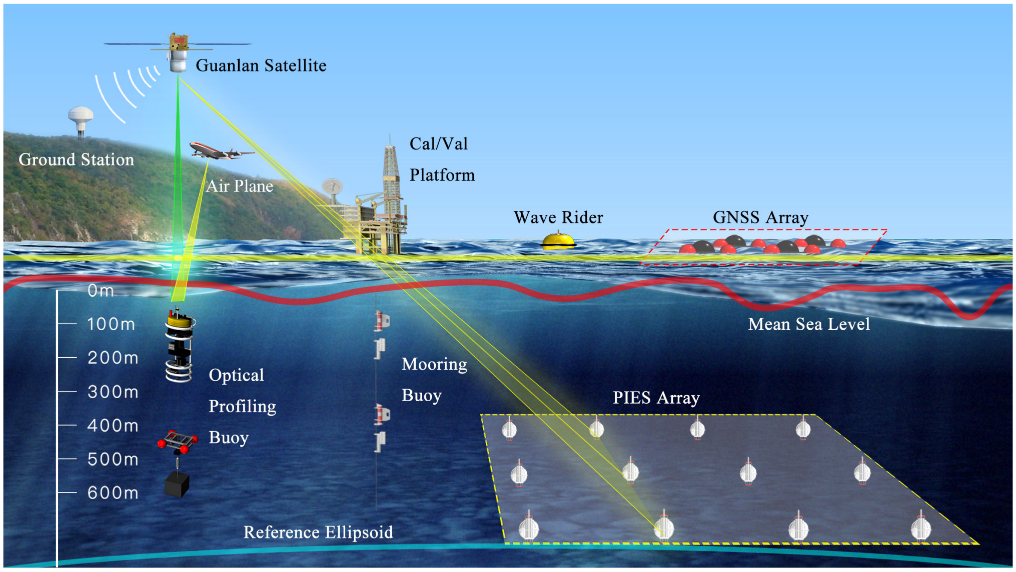

FIGURE 10 | A schematic illustration of calibration/validation facility for the Guanlan IA and OL.

and meteorological sensors. To make a simultaneous validation of SSH in two dimensions at submesoscales, a multi-sensor array will be deployed by means of integrating the PIES (pressure inverted echo sounder), the GNSS buoys, as well as a combined glider/mooring system. The pixel-wise difference of SSH between the Guanlan IA and the validation field array can therefore be calculated, resulting in a quantitative evaluation of the error budget specified in **Table 4**.

The spaceborne OL will mainly be calibrated by an airborne lidar. Based on the satellite orbit and laser emission direction, the trajectory of laser footprint (50–80 m for the two science orbits given in **Table 2**) at the sea surface can be calculated. The airborne lidar verification experiment is then carried out synchronously with satellite measurement in the trajectory direction. A flight altitude of about 4 km results in a ground path of greater than 50 km, and the trajectory deviation between the footprints of airborne and spaceborne lidars at the sea surface is expected to be less than 2 km. The time deviation between measurements from the two platforms will be less than 0.5 h. Aside from aircraft-based measurements, the calibration method based on the comparison between ocean surface signal and theoretical results (e.g., Cox-Munk theory) using wind speed or surface cross section derived from the radar is also feasible.

TABLE 4 | Parameter and accuracy for the Guanlan IA/OL *in situ* validation system.

Instrument	Parameter	Accuracy*
Interferometric altimeter validation	Absolute SSH	2.5 cm
	Relative SSH	0.5 cm
	Significant wave height	<20 cm
	Wind speed	<0.5 m/s
Ocean lidar validation	Maximum depth	≥300 m
	Vertical resolution	<1 m
	Backscattering coefficient	<5%
	Chlorophyll concentration	<5%

**All values are applicable to the sea surface or the ocean interior for the validation of IA and OL, respectively.*

The validation of the Guanlan OL requires simultaneous measurements of the subsurface ocean by the laser satellite and an integrated optical buoy (**Figure 10**). To do so, an optical multi-parameter profiling system is developed using an automatic winch, along with a ship-borne lidar. The optical buoy will be deployed at the footprint of the satellite orbit, and continuous profiling observations will be carried out when the satellite overflies it. The maximum depth of the profile will exceed 300 m (almost twice as much as the usual penetration depth of an OL) and the vertical resolution will be less than 1 m. Multiple parameter measurements of temperature, salinity, chlorophyll concentration, backscattering coefficient and so on, will be collected and transmitted to the data center in near real time, where an integrated Cal/Val of the Guanlan OL will be implemented in order to reach the level of precision and accuracy described in **Table 4**.

UNIQUE CHARACTERISTICS AND POTENTIAL BENEFITS

The payload system of the Guanlan science mission has a few unique technological characteristics and potential scientific contributions:

First, a unique combination of two active sensors of IA and OL (**Figures 4**, **5**), which to our knowledge is the first of its kind in ocean satellite missions. The joint use of active microwave and lidar technologies will allow an integrated sensing of dynamic and biological properties, opening a new window for the cross-disciplinary study of the ocean. Meanwhile, the simultaneous functioning of the IA/OL system will allow an enhanced correction of the contaminations of the atmosphere and the air-sea interface which in turn effectively reduce the error budgets of the two sensors.

Second, the dual-frequency (Ku and Ka) IA, benefiting from a wider swath and a shorter repeat cycle, will lead to a substantially improved temporal and spatial resolution up to days and kilometers. The Guanlan satellite in combination with other IA missions including SWOT will hopefully serve as an observational foundation for submesoscale oceanography. In addition, oceanic precipitation is known to have very distinct impacts on the transmission of Ku- and Ka-band microwaves, on the basis of which rain-induced errors may be significantly reduced by using a dual-frequency technique. As far as ocean waves are concerned, the two bands also have different resonant frequencies, thus widening the wave spectrum that can be effectively resolved.

Third, as one of the first spaceborne OLs and an oceanic counterpart of CALIPSO, the Guanlan OL will be used as an experimental sensor to test a number of new ideas such as a replacement of the nadir-pointing conventional altimeter, a complementary sensor measuring the ocean component of the global carbon cycle, a new sensor demonstrating the feasibility of optical-acoustical conversion in the ocean, and an extended sensor tracing the paths of terrestrial dust into the ocean as well as its biogeochemical effects.

OUTLOOK AND RECOMMENDATIONS

To Contribute to and Benefit From the Era of Big Marine Data

The era of big marine data arrived in the early 2010s with nearly half of the contributions coming from satellite observations (Overpeck et al., 2011). Specifically, however, the majority of these remote sensing data come from visible and infrared sensors, while those from microwave instruments remain small due to the well-known limitations of coarse spatial resolution. The Guanlan altimetry, along with SWOT and other on-going and forthcoming missions of a similar nature (the wide swath imaging altimeter) will lead to a $\sim 10^4$ increase in the daily altimetric data volume, while the intrinsic problem of poor sampling (particularly the along-track/cross-track asymmetry) associated with conventional altimeters will be largely resolved. This will mark the transition from the semimesoscale "grid" phase to submesoscale "pixel" phase in satellite altimetry, making a revolutionary contribution to modern sea level measurement as represented by a seamless coverage of the entire globe for the first time. In addition, if it downlinks data over land, it will be the first global measurements of snow depth measurements from a difference in the Ka/Ku band radar. It will therefore be a great contribution to the study of the cryosphere and snowfall.

It has to be recognized, however, that the volume of daily marine data acquisition is highly inhomogeneous in the vertical dimension: reducing from the level of petabyte at the sea surface to the level of kilobyte near the deepest ocean bottom. In other words, the ocean has entered the big data stage at the surface while it still remains in the small data stage at the bottom. The coexistence of big and small data in terms of ocean measurements is expected to last for a long time. As such, persistent availability of global ocean optical profile data from the Guanlan OL down to the depth of the maximum penetration appears to be extremely valuable, making a unique contribution to the observation of the oceanic mixed layer. It will also benefit by combining with concurrent *in situ* surface drifters and Argo floats to routinely provide a systematic monitoring of the upper ocean between 0 and 2000 m.

In the time domain, it is understood that the probability of detecting new or changing small scale oceanic features increases constantly with observational time (Wilson et al., 2010), because a higher signal-to-noise ratio can be statistically obtained with longer time series. The wider swath of the Guanlan IA ensures a shorter repeat cycle (and hence an extended time series) compared to SWOT or the conventional altimeter constellation. As pointed out by Scott et al. (2010), one would need more than one SWOT mission to capture the temporal variability of the ocean at submesoscales. The combined effect of shorter temporal resolution and a longer time series will hopefully help to enhance the characterization and eventually the prediction of oceanic features, from climate scales to weather scales, which is a significant step forward in modern dynamic oceanography.

Given the coexistence of big and small data in ocean science to date, particularly the highly inhomogeneous sampling as a function of depth (which limits us to capture only a very small fraction of the total vertical ocean variability), we would like to argue that no observation system is redundant for at least the next few decades. Similar to the metro system in a metropolitan, we are still at a very early stage with a single line of underground in operation. The traffic problem can be effectively alleviated only when a properly distributed network is fully established.

To Open a New Window for Interdisciplinary Studies of the Ocean

Interconnection among the physics, biology, and biogeochemistry of the ocean is a fundamental feature which occurs at a wide range of temporal and spatial scales. Typical examples include (but not limited to) coastal upwelling, El Niño/La Niña, Pacific Decadal Oscillation and so on. A very strong manifestation of physical-biological-biogeochemical interactions/covariations takes place at the oceanic mesoscale, the mechanisms of which necessitate the use of multidisciplinary approaches (Chelton et al., 2011a; McGillicuddy, 2016). Recent progress in automated methods for identifying and tracking individual eddies globally, with merged satellite altimeter data, has opened a new window to examine these interdisciplinary couplings in eddy-centric coordinates at an unprecedented semimesoscale (∼50 km).

Normally, a mesoscale eddy is a rotational water column that extends to hundreds (even exceeding one thousand) of meters in the upper ocean through the so-called Ekman spiral, mixed layer, mirror layer (Chen and Geng, 2018), and pycnocline (thermocline, halocline) layer, as well as acoustic waveguide in hydrodynamics and geophysics, and the photic zone and the compensation layer in biological oceanography. An ideal strategy for eddy observation is to simultaneously capture its surface signature along with its interior structure. This forms a key motivation of the Guanlan science mission, which integrates the capacity of microwave remote sensing (via IA) to measure the surface dynamic topography, and the advantage of optical (lidar) remote sensing (via OL) to profile the internal biological aspect of the eddy properties. It should be stressed that such cross-disciplinary studies are greatly facilitated by recent advances in artificial intelligence techniques for big data analytics.

To Serve as a Bridge to Better Link Model With Observation

Observation (both *in situ* and remote sensing) and modeling are the two most powerful tools in support of modern oceanography. Obviously, their roles will be maximized when they have properly matched spatiotemporal scales. The concept of eddy-resolving numerical models was initialed in the 1990s (Semtner and Chervin, 1992), which is largely in pace with the mesoscale resolving (∼100 km) capability of satellite altimetry (Fu et al., 1994). With the rapid development of computing power, basin scale numerical simulations have crossed the threshold of submesoscale (∼10 km) around the turn of this century (Smith et al., 2000). The best spatial resolution of merged altimeter data to date, however, has stuck at the semi-mesoscale, left far behind the ocean model resolution. There is concern that the long-time mismatch between model and observation will slow down and eventually limit the development of ocean modeling.

Fortunately, this situation is likely to be dramatically changed with the scheduled launch of SWOT in 2021, and will be further improved by other follow-up missions including Guanlan. With this new generation of spaceborne interferometric imaging radars, the altimeter resolution is expected to catch up with the model resolution at ∼10 km level on a global scale, thus rebalance the bridge between observation and numerical modeling as far as sea level is concerned. The implication of this advancement is going to be profound: while mesoscale eddies are responsible for ∼50% of horizontal heat and substance transport in the ocean, variabilities at submesoscale (e.g., fronts and filaments) account for about half of the total vertical transport (Lindstrom et al., 2010). Vertical velocities associated with divergences and convergences of geostrophically balanced velocities on 10 km scale penetrate down to a few hundred meters below the ocean surface (Lapeyre et al., 2006). This will enable the vertical transfer of heat, nutrients, and dissolved CO_2 to be resolved via SSH, paving the way to a new era of submesoscale oceanography, which might be a significant breakthrough for marine science in the 21st century.

To Demonstrate the Feasibility of Direct Satellite Sensing of Marine Life

The essential oceanographic variables that can be measured from space by prevail sensors (visible, thermal infrared, and microwave) include sea surface temperature, ocean salinity, SSH, vector wind, sea state, ocean color, and sea ice (Bonekamp et al., 2010). As far as ocean color and marine ecosystem are concerned, persistent cloud cover, periods of constant night and prevailing low solar elevations in polar regions severely limit traditional passive satellite ocean color measurements, and leave vast areas unobserved for many consecutive months each year. The advent of lidar technology creates an unprecedented opportunity/possibility for laser remote sensing of the ocean in at least two aspects: (i) Reveal depth resolving (instead of vertically integrated) optical properties of nearly the entire subsurface oceans including the polar regions, as demonstrated by CLIPSO; (ii) Directly detect signals of ocean animals, both community and individual, in the subsurface ocean. The potential ability to detect marine life and their food web from space will set a very significant milestone in the development of ocean remote sensing. Such a dream has never been so close as today: the lidar footprint of the Guanlan satellite is comparable to the size of big fish who favor to stay in the subsurface ocean between 0 and 200 m (which properly matches the penetration depth of OL). As a result, it is highly anticipated that we will soon enter the period of life signal identification and even animal trajectory tracking from space in the coming decade.

In summary, the key objectives of the Guanlan science mission are to resolve SSH at submesoscales, globally, using IA, and to extend the penetration depth of space-borne OL to the vicinity of thermocline, moving a critical step forward toward an ultimate goal of an "transparent ocean" which relies on fine resolution, full spectrum, and multidisciplinary oceanographic sensing and observation. Meanwhile, an integrated physical-biological measurement of the ocean will be achieved by effectively combining advanced laser and radar technologies, serving as China's novel contribution to the international ocean remote sensing and space oceanography communities.

AUTHOR CONTRIBUTIONS

GC and LW conceived and designed the review. YX, YZ, and JL contributed to the interferometric altimetry. SW and WC contributed to the ocean lidar. JT and FY contributed to the calibration and validation. CZ and CM contributed to the orbit design and sampling strategy. GC, YZ, WC, FY, and CM wrote the manuscript. All authors reviewed the manuscript and approved it for publication.

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Globally Consistent Quantitative Observations of Planktonic Ecosystems

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In this paper we review the technologies available to make globally quantitative observations of particles in general—and plankton in particular—in the world oceans, and for sizes varying from sub-microns to centimeters. Some of these technologies have been available for years while others have only recently emerged. Use of these technologies is critical to improve understanding of the processes that control abundances, distributions and composition of plankton, provide data necessary to constrain and improve ecosystem and biogeochemical models, and forecast changes in marine ecosystems in light of climate change. In this paper we begin by providing the motivation for plankton observations, quantification and diversity qualification on a global scale. We then expand on the state-of-the-art, detailing a variety of relevant and (mostly) mature technologies and measurements, including bulk measurements of plankton, pigment composition, uses of genomic, optical and acoustical methods as well as analysis using particle counters, flow cytometers and quantitative imaging devices. We follow by highlighting the requirements necessary for a plankton observing system, the approach to achieve it and associated challenges. We conclude with ranked action-item recommendations for the next 10 years to move toward our vision of a holistic ocean-wide plankton observing system. Particularly, we suggest to begin with a demonstration project on a GO-SHIP line and/or a long-term observation site and expand from there, ensuring that issues associated with methods, observation tools, data analysis, quality assessment and curation are addressed early in the implementation. Global coordination is key for the success of this vision and will bring new insights on processes associated with nutrient regeneration, ocean production, fisheries and carbon sequestration.

Keywords: plankton, imaging, OceanObs, autonomous platforms, global observing, EOVs, ECVs

1. CONTEXT AND RATIONALE WHY SHOULD WE OBSERVE PLANKTON AND PARTICLES IN THE OCEAN?

Plankton are organisms that have either null velocities or velocities significantly smaller than oceanic currents and thus are considered to travel with the water parcel they occupy (some can, however, through vertical swimming or change in buoyancy, move between water masses). Plankton are an extremely diverse group, spanning across several orders of magnitude in size (sub-microns to several a meter) and with representatives from all trophic levels (auto-, mixo- and hetero-trophic) and all domains of life, including bacteria, protists and small to large metazoa. Knowledge on distribution patterns and composition of planktonic communities is of great interest for many reasons: (1) Life is thought to have begun in the ocean, and planktonic organisms therefore provide important evolutionary insights on diversity, complex life forms and adaptations to highly variable environments. (2) Plankton form the foundation of most marine food webs, with phytoplankton accounting for approximately 50% of global primary production. The organic material produced by phytoplankton is consumed by herbivorous zooplankton that provide a crucial source of food for higher trophic levels, including important commercial species, marine mammals and sea birds. (3) Many important commercial species have early developmental stages that are planktonic. Time spent in the plankton is often considered a time of greatest vulnerability and hence a bottleneck for recruitment. (4) Planktonic organisms play important roles in global cycles of the majority of oceanic elements. (5) Because of their restricted environmental preferences and relatively short life spans, plankton abundance and composition react tightly to local and global environmental changes (e.g., Mackas and Beaugrand, 2010; Beaugrand et al., 2013, 2015; Edwards et al., 2013), and can serve as sentinel organisms of environment and water quality changes, and (6) some planktonic organisms can be toxic or cause disease and parasitism in animals, including commercial ones (Anderson et al., 2019). Given these important functions, the biomass and diversity of phytoplankton and zooplankton were identified as Essential Ocean Variables (EOVs) by the Global Ocean Observing System (Chiba et al., 2018; Miloslavich et al., 2018; Muller-Karger et al., 2018; Bax et al., 2019) as well as Essential Climate Variables (ECVs) under GCOS (Global Climate Observing System).

In addition, the upper ocean is teeming with organic and inorganic particles which can form larger aggregates (marine snow) very often colonized by micro-organisms. These aggregates can sink rapidly, creating one of the major fluxes of matter to the deep ocean (e.g., Kiko et al., 2017), forming the base of the food web in this dark ocean, and are an important vector in controlling nutrient distribution across the ocean. Recognizing this role, particulate matter was also identified as an EOV and ECV. In particular, the concentration of particulate matter provides quantitative information on spatial gradients and temporal variations in total particulate substrates, which are mostly comprised of organic material in the open ocean.

Understanding how plankton communities change at regional and global scales, which is critical to address ocean health, food security, and biogeochemical cycles, requires a multidisciplinary approach to ecology. While planktonic organisms have been studied in great detail for decades, the relatively inconsistent and diverse use of various methods and techniques (taxonomic, isotopic, genomic, biogeochemical, etc.) makes it difficult to uncover global and/or long-term patterns and trends in abundances, diversity and composition of the plankton. As a result, global analyses are to date restricted to basic descriptors of plankton such as total abundance or biomass. For instance, phytoplankton distributions are most often described through chlorophyll *a* measurements and the concentrations of other pigments, which provide, through empirical relationships, limited taxonomic and size information on phytoplankton communities (Swan et al., 2016). Knowledge of the distribution of larger organisms often relies on the collation of numerous and heterogeneous observations from several decades and from diverse samplers, providing a crude description of zooplankton total biomass at a global scale (e.g., Moriarty and O'Brien, 2013; Moriarty et al., 2013; O'Brien et al., 2017) or through empirical relationships between several planktonic groups (Buitenhuis et al., 2013), with only little concern about diversity. Hence, our general understanding of plankton abundance and diversity is highly fragmented due to a paucity of data, heterogeneity among collection methods, analysis techniques, technology and scale of measurements. It is also fragmented because there is a lack of standardization of methods, data outputs and data curation.

Recently, new sensors, instruments, platforms (e.g., Argo floats see Roemmich et al., 2019, and gliders see Testor et al., 2019) and methods (imaging, acoustics, omics, etc.) have been developed and deployed to improve the spatiotemporal resolution of planktonic communities and particles (Powell and Ohman, 2015a; Brownlee et al., 2016; Hunter-Cevera et al., 2016; Ohman et al., 2018) even in hostile conditions (Grossmann et al., 2015). Here we suggest that with these technologies (as well as concurrent advances in software), we have the ability to collect and analyze significantly more global information on plankton distributions and diversity and at a finer scale (taxonomic, spatial, and temporal) than is currently done. Such a global plankton observation effort is not intended to replace fine, high-quality and highly precise local sampling and observations, usually done during specific oceanographic cruises focused on process studies or long-term observation sampling. Rather, the goal is to expand and upscale our observational capabilities at larger scales and with consistent data to provide a sustained observing system. To do so, we propose leveraging on existing international coordinated sampling programs and infrastructures (e.g., GO-SHIP Sloyan et al., 2019, OCEAN-SITES, Argo) by adding supplemental measurements that could be carried out without major changes to current sampling. In addition, integrating those supplementary measurements into existing long-term surveys would allow the description of key elements of the plankton system at both local and global scales.

This article is organized as follows; we first review the state of the art for plankton sampling in general and imaging in particular, focusing on commercially available instruments for operational reasons. We then detail what could be expected from a global plankton sampling program. We identify challenges associated with such a program and finally make recommendations on how to proceed over the next decade.

2. STATE OF THE ART

There are no global standard methodologies for the quantification of plankton across the different plankton groups (e.g., phyto-, zooplankton) or within each group. Few exceptions are analytical chemical methods, such as phytoplankton pigment analysis using HPLC and the use of WP2 nets from 0 to 200 m for zooplankton field sampling (UNESCO, 1968). This partly explains why existing plankton time series observations are difficult to compare except in their trends (O'Brien et al., 2017), since they are based on different methodologies and taxonomic resolution. Physical and biogeochemical marine research have systematic and sustained sampling programs that, at times, measure plankton-related variables, albeit at a low taxonomic and functional resolution (e.g., diel vertical migration pattern from acoustic Doppler current profilers, total *in vivo* fluorescence allowing the estimation of chlorophyll *a* concentrations). For decades physical and biogeochemical marine research has been tightly coordinated at the international level (e.g., GO-SHIP, GEOTRACES, OCEAN-SITES), which has not been the case for biological and ecological marine research.

One exception is the plankton-relevant data available from ocean color passive remote sensing, which provides global information on the distribution and concentration of chlorophyll *a*, organic carbon and phytoplankton carbon distributions in the surface ocean on a near-daily time scale (Siegel et al., 2013). Unfortunately, data are limited to the upper ocean and are only continuously available since 1996 (for a future perspective see Groom et al., 2019). Methods to obtain taxonomic and size information from remote sensing have been proposed (e.g., Alvain et al., 2008); however, these methods in general lack validation, and it is unclear if it is possible to use remote sensing to gain information about phytoplankton size and taxonomy beyond that which is globally correlated to chlorophyll (Chase et al., 2017). Recently, it has been shown that active remote sensing with atmospheric LIDAR (Light Detection and Ranging), not specifically tuned for ocean observations, can provide a proxy of concentration of upper ocean particles, even during the polar night and through thin cloud covering (Hostetler et al., 2018).

Another exception is the Continuous Plankton Recorder (CPR) surveys (Batten et al., 2003, 2019). CPR has the most extensive spatial coverage of any plankton sampling program and provides taxonomically resolved abundance data. Commercial ships or other ships-of-opportunity tow the CPR along their regular routes in near-surface waters (Batten et al., 2003). Lengthy and consistent time series exist for several locations such as the North Atlantic and North Sea (> 60 years), the Southern Ocean (> 25 years) and the North Pacific (19 years) as well as more recent regional surveys in the Mediterranean and around Australia, for example (Batten et al., 2019). It is, to date, the most cost-effective way to sample ocean basins over large distances. However, CPR sampling occurs at relatively low resolution (each sample represents 18.5 km of ocean), is confined to the surface ocean, and currently poorly covers the tropics and the sub-tropics (i.e, no global coverage). While the CPR is an internally consistent sampler, not all planktonic groups are well sampled or well resolved (very small, very large and/or fragile plankton especially), so abundance estimates are best considered as semi-quantitative, and integration with other data sources requires careful treatment (Richardson et al., 2006). Nevertheless, the existing lengthy CPR time series is invaluable and should be incorporated into continuing assessments of changing ecosystems.

3. MEASUREMENTS WITH INCREASING CAPABILITIES

While discrete water samples, net tows, CPR and ocean color provide important data for the study of oceanic plankton on basin scales, they are far from sufficient in their taxonomic, spatial and temporal resolution. There is a clear need for a systematic and sustained global sampling program that will take advantage of technological advances that provide significantly more taxonomic information. Such a program will likely build on the current standard measurements, expanding them to a wider range of pelagic systems, to a finer spatial, temporal and also functional/taxonomic resolution by incorporating the growing field of -omics and the expanding suite of autonomous sensors and quantitative imaging technologies.

In this section, we provide a list of existing sampling technologies for plankton. While all have achieved a technology readiness level (TRL) beyond the prototype stage, some of these technologies are more mature than others. Assessment of TRL depends, among other things, on method of deployment (e.g., AUV vs. R/V), but we avoid getting into these details here. Much about the TRL of a specific technology for a specific application can be assessed from the literature provided. Literature emanating from groups who have not developed the technology is particularly useful to assess the operational status of a given technology.

3.1. Analysis of Water Samples

Discrete sample analysis is performed on water samples taken from CTD-rosettes, surface buckets, water pumped from the surface into vessels (flow-through systems) and plankton nets. Such analyses often target the bulk properties of the underlying particle/plankton population, including chemical analysis of mass and elemental content, pigment content, size distribution and genetics.

3.1.1. Bulk Mass and Elemental Composition

Total suspended mass in the upper open ocean is dominated by plankton-derived particles. The analysis of organic carbon, phosphorous, nitrogen and micro elements associated with bulk particulate samples retained on a filter provides essential descriptors of the dynamics of such particles. The associated methods have been determined and refined for decades (e.g., Hurd and Spencer, 1991; Cutter et al., 2017).

3.1.2. Diagnostic Pigments

Information on phytoplankton diversity can be gained from High Performance Liquid Chromatograhy (HPLC) analysis of pigments present in bulk samples. Whereas, chlorophyll *a* is present in all phytoplankton (although in its divinyl form in prochlorophytes) and typically used as a proxy of phytoplankton biomass, accessory pigments vary with phytoplankton community composition, and some pigments can be used as biomarkers of specific taxa (Gieskes and Kraay, 1983; Jeffrey et al., 1997; Roy et al., 2011). Several pigment-based approaches have been proposed that allow estimating the relative contribution to chlorophyll *a* of different phytoplankton taxa (CHEMTAX algorithm Mackey et al., 1996) or taxonomic groupings or size classes (Claustre, 1994; Vidussi et al., 2001; Uitz et al., 2006; Aiken et al., 2008). Pigment-based methods have the advantage that they cover the whole phytoplankton assemblage in a single analysis and provide a quantitative assessment of phytoplankton community composition at the level of class or higher (Bax et al., 2001). However, lacking flow cytometry and microscopy validation, these methods can have large uncertainties linked to variability in accessory pigmentation within a given taxon or induced by environmental factors (Henriksen et al., 2002; Laviale and Neveux, 2011). It is also recognized that some biomarker pigments are not restricted to one single taxon, leading to ambiguity in the discrimination of some phytoplankton groups. Chlorophyll *a* can also be estimated from fluorometric and spectrophotometric analysis; however, such data can be significantly different from determination obtained with HPLC and are not recommended as a standard. However, they have significant value in conjunction with long-term time-series, where they have been used for years.

3.1.3. Genomic and Next Generation Sequencing

Next generation sequencing (NGS, also called high throughput sequencing, HTS) provides relatively cost-effective and fast sequencing of DNA and RNA. Initially developed for microbial ecology, and now applied to any drop of water, it has been progressively applied to the whole marine ecosystem (e.g., metabarcoding, metagenomics, metatranscriptomics), encompassing plankton, nekton and even benthic organisms. Barcoding targets and amplifies a specific sequence that is highly conserved yet variable across taxa, such as the 18S ribosomal DNA or cytochrome oxidase (COI) genes for eukaryotes, in order to identify a specific organism. Metabarcoding (MetaB) is the application of barcoding at the scale of a whole water sample and allows the classification of organisms either expressed as in Operational Taxonomic Units (OTU) whose DNA is present in a given sample (Bucklin et al., 2016) or assigned to different taxa through the comparison with databases of named reference sequences. They represent the principal way of addressing biodiversity for prokaryotes and, to some extent, for pico- and nanoeukaryotes as well. Similarly, metagenomics (MetaG) allows the study of all genes present in a given water sample, giving access to the reconstruction of full genomes (Metagenome-assembled genomes or MAGs) for non-model and uncultivated organisms (e.g., Delmont et al., 2018; Tully et al., 2018). RNA sequencing through transcriptomic and metatranscriptomic (MetaT) methods provides new insights into gene expression, and DNA or RNA sequences converted to amino acid sequences (e.g., proteins) allow the characterization of protein structures and phenotypic variations across planktonic communities (e.g., Carradec et al., 2018). These techniques can also be applied at the individual level of a single cell, giving new insight on the genomes and their expressions of uncultured species.

MetaB requires gene amplification using primers that attempt to be as universal as possible, but may still lead to differential amplification of some organisms, whereas MetaG could exhibit biases associated with the length of reads obtained through HTS (although long-read sequencing is currently being developed, it currently has a relatively high level of sequencing error). Due to these different steps, -omics methods provide results that, at present, should only be considered as relative, or semi-quantitative at best (e.g., Bucklin et al., 2016). Another limitation of these methods is the lack of reference sequences in databases, although the reconstruction of MAGs from MetaG data could partly overcome this issue.

MetaB and "environmental" DNA (eDNA) analyses, since they allow estimation of the diversity of samples with unprecedented taxonomic resolution and have become relatively affordable and automated (Ji et al., 2013), have the potential to be used in global surveys to address the diversity of organisms. However, they may not yet be ready nor affordable for large-scale ecosystem surveys (Deiner et al., 2017), while the complexity of analyzing the resulting data remains a challenge. In fact, 10 years ago (Bowler et al., 2009) predicted that miniaturized ecogenomic sensors able to monitor almost all planktonic DNA and RNA would allow near real-time measurements of microbial activity in the ocean and associated biogeochemical processes such as carbon flux. However, such an achievement has not yet been reached, but the recent development of Oxford Nanopore MinION sequencing (Jain et al., 2016; Lu et al., 2016) and its first applications in the marine environment (Warwick-Dugdale et al., 2018) indicate that this possibility may become available soon.

3.2. Sensors

Sensors measuring bio-acoustical and bio-optical properties (see below) have been mounted on CTD-rosette frames, undulating vehicles, autonomous vehicles and floats, ship hulls (for bio-acoustics) and in-line flow-through systems (bio-optics). All sensors require calibrations to obtain absolute physical values comparable across instruments and proxy-calibrations to convert signals to biogeochemical parameters, as these measurements provide a proxy—not a direct—estimate of variables of interest. This is because while the forward problem is well defined (e.g., predict the acoustical or optical signal measured given a field of known organisms with specific optical or acoustical characteristics), the inverse problem is not (i.e., there are many possible configurations of organisms that could result in the observed signal; some, however, are more likely than others if we have additional knowledge). Hence, these methods are more useful when deployed in conjunction with other measurements.

3.2.1. Bio-Acoustics

Acoustic methods can reveal much about the spatial distribution and temporal dynamics of zooplankton. For example, echosounders led to the discoveries of the diel vertical migration of plankton and micronekton (Johnson, 1948) and their ubiquitous and dense but previously hidden aggregations (Cheriton et al., 2007). The ability of acoustic tools to simultaneously assess animals ranging in size from sub-mm to m allows ecological processes in the plankton to be examined (Kaartvedt, 2000; Ballón et al., 2011; Benoit-Bird and McManus, 2014; Powell and Ohman, 2015b) when appropriate frequencies are chosen. However, this ability also highlights a key challenge—separating animal types and accurately assessing the biomass of each. While these approaches have long been used for fish stock assessment and management of a number of species (MacLennan and Simmonds, 1992), in plankton, dramatic differences in body size, species composition, elastic properties of the animals and orientation markedly influence the acoustic reflectivity or target strength (Roberts and Jaffe, 2008; Briseño-Avena et al., 2018), coupled with the complexity of the community, making separation of taxa and assessment of biomass difficult. To address these challenges, research efforts have recently shifted from adding additional narrow-band signals (e.g., Holliday et al., 2009) to utilizing a continuum of frequencies to increase the amount of information available from acoustic returns (e.g., Jech et al., 2017). Acoustic measurements, however, will always have uncertainties; many of the greatest insights on zooplankton resulted from creative integration of multiple, complementary sampling devices including acoustics with nets, optics, imaging and animal tagging to take advantage of the different strengths and fill in the gaps of each approach (reviewed in Benoit-Bird and Lawson, 2016). Multi-sensor fusion efforts have the potential for wider application through the use of autonomous platforms, which resolves the limited range issue of high frequency acoustics. While bio-acoustic instruments have only begun to be deployed over long periods of time on autonomous platforms (Powell and Ohman, 2015a,b), we expect that strong development and wide use of these instruments will be seen in the next decade (Benoit-Bird et al., 2018).

3.2.2. Bio-Optics

Like acoustic, optical measurements are best used with complementary sampling approaches. Measurements of the optical characteristics of water (e.g., absorption, scattering, attenuation and fluorescence) *in situ* have been used for decades (e.g., Gardner et al., 2018) to characterize bulk properties associated with micrometer-size particles in general and phytoplankton in particular (near-forward scattering extends this range to a few 100 μm). Deployed on profiling floats, gliders, moorings, CTD rosette frames and in-line systems they are capable of providing high-resolution information on the spatial distribution of phytoplankton but with little specificity in terms of composition. They can also provide information on a few pigments beyond chlorophyll *a* (Chekalyuk and Hafez, 2008; Proctor and Roesler, 2010; Chase et al., 2013) which have been used to provide estimates of phytoplankton functional groups (e.g., MacIntyre et al., 2010; Houliez et al., 2012). Data on basin scales from in-line systems and BGC-Argo floats have become available (Boss et al., 2013; Rembauville et al., 2017), which is useful, for example, to validate satellite-based algorithms (Werdell et al., 2013; Haëntjens et al., 2017). These techniques are also useful as proxies of particulate organic carbon in general and phytoplankton carbon in particular (Cetinić et al., 2012; Graff et al., 2015). Bio-optical sensors are more sensitive to fouling and require periodic cleaning or bio-shutters. Simple measurements, such as the Secchi disk, have been very useful to characterize the optical status of the upper ocean including long-term changes of plankton (Boyce et al., 2010).

3.3. Particle Size Distribution

Particle counters are designed to count particles and obtain information on their size. There are two main types of particle counters: (1) Electronic particle counters measure the change in impedance as an estimate of the physical volume occupied by a particle while it passes through a small aperture (Coulter et al., 1966; Graham, 2003). (2) Optical counters are based on shadow (HIAC counters and the LOPC, the latter no longer commercially available) or near-forward scattering of a laser beam as it encounters particles (Sequoia's LISST). While many of these technologies have been around for decades, in recent years the LISST has been successfully deployed in open ocean environments on CTD rosette frames (Reynolds et al., 2010;

Barone et al., 2015; Leroux et al., 2018) and in flow-through systems (Boss et al., 2018). Note that optical counters are primarily sensitive to the cross-sectional area of particles while the resistance-based particle counter size is based on particle volume, hence the specific size associated with the particles, based on an equivalent sphere, is different in both cases. Additionally, handling and hydrodynamics associated with delivering the sample to the sizing instrument can affect the size determined, due to aggregation/disaggregation processes in the sample prior to sampling. Hence, some researchers intentionally disaggregate the sample prior to measurement (Milligan and Kranck, 1991).

3.4. Analysis of Individual Organisms and Particles

Imaging of individual organisms and particles, as long as the volume analyzed is well quantified, makes it possible to obtain simultaneously: (1) abundance of the different groups of plankton and their relative contribution to total abundance and biomass, (2) morphological or optical measurements on the organisms that can be used to obtain their biovolume as a proxy of their biomass, but also to derive size spectra of the imaged objects and (3) production of a digital archive of images and optical properties that can be shared or reprocessed if more information is needed. In addition, imaging systems can be operated on fresh samples on research vessels or *in situ*, as well as on concentrated or fixed samples. In some cases, images may reveal behavioral information (e.g., predator-prey interactions, parasitism, diurnal vertical migration) as well as physiological state and population conditions, from which rates may be inferred (e.g., lipid content and egg-production rates of ovigerous copepod species, Möller et al., 2015; growth rate of phytoplankton species, Dugenne et al., 2014).

Since the 1980s, a considerable amount of energy has been directed to produce prototypes of automated quantitative imaging devices [see reviews in Foote (2000), Wiebe and Benfield (2003), Benfield et al. (2007), Sieracki et al. (2010), Stemmann and Boss (2011)], among which some are now commercially available (**Table 1**). Some global patterns in large plankton communities and/or particle fluxes have emerged from intense use of these devices during ship surveys (Stemmann et al., 2008b; Bonato et al., 2015; Guidi et al., 2015; Thyssen et al., 2015; Biard et al., 2016; Waite et al., 2016) or on high frequency platforms (Thyssen et al., 2008, 2014). These instruments can be used *in situ*, in the laboratory and/or on a research vessel depending on their design, but they all share some common principles. Marine particles and plankton either pass by or are placed in a known volume illuminated by a specific light source. For optical devices, various optical measurements are made (e. g., fluorescence), while for imaging devices a picture is taken and measurements inferred from the picture (both could happen for the same object in the case of imaging flow cytometers). Images can be classified according to taxonomic or functional groups and living cells can be separated from aggregates and other non-living particles.

Imaging devices also provide common particle characteristics: each object's size, shape and cross-sectional area can be determined as well as the intensity of light coming from each pixel of the particle, identified thanks to its optical or image characteristics, producing a large amount of raw data. Sometimes, these data are used to provide statistics for a given group (e.g., flow cytometry) or for given sizes. Each optical/imaging technique also comes with its own size range limitation (**Table 1** and **Figure 1**). Small particles are often too small to be imaged efficiently (too few pixels, signal below threshold or near noise level), while larger organisms are too scarce to be sampled quantitatively (volume analyzed is too small), or too large to pass by the tubing of some devices, resulting in a narrow size range compared with the theoretical one (**Figure 2**). This "effective" range is often missing from technical documentation and needs to be determined experimentally. Additionally, to obtain taxonomic information from optical or imaging methods, there is a need for a computer-assisted human expert to classify organisms based on their optical properties (e.g., "gating" in flow cytometry) or on their image. While machine-learning methods are getting progressively more efficient (Luo et al., 2017), the final taxonomic resolution is often limited, and may include substantial errors (Culverhouse et al., 2003, 2006). The increased capabilities in automated recognition of images still needs to be complemented with taxonomic expertise. Training libraries associated with specific technologies are expanding and could be refined to be applied to new datasets as well as to revisit old datasets. This ensures that the taxonomic knowledge is preserved in the form of image libraries, in a fashion similar to plankton identification field guides (but not quite as rigorous as taxonomic keys). Finally, strong analytical and programming skills as well as computer resources are needed to sort and analyze these often very complex data, which combine organisms' taxonomic, morphological and optical properties together with their concentration.

3.4.1. Flow Cytometers

Flow cytometry measures fluorescence and scattering signals from single virus, bacterial or protistan cells contained in a seawater sample. Flow cytometry fluidics are designed to orient individual particles through a capillary where they are illuminated sequentially by one or several laser beams. The scattering signals (forward and side scattering, FSC and SSC) accompanied with different fluorescence signal intensities are recorded for each individual object. Fluorescence is either natural to the cell (e.g., photosynthetic pigments) or originating from a specific stain (e.g., SYBR green stains, which bind to DNA). Therefore, flow cytometry can record simultaneously on the same particle several features representative of its size (FSC), granularity (SSC) or pigment quantity and composition (fluorescence). Note, however, that SSC depends on size, but also shape and refractive index of the analyzed cell (Green et al., 2003; Agagliate et al., 2018), and without a proper calibration against cells similar to the ones present in a sample (e.g., Laney and Sosik, 2014), the size of particles inferred from FSC could be significantly biased. Different populations of particles sharing similar characteristics are often lumped (a human-based "gating" step) to represent sub-populations of the underlying assembly.

TABLE 1 | Comparison of the different optical and imaging methods commercially available with a focus on their different size targets (expressed as equivalent spherical diameter; ESD, both commercially available and determined as efficient for quantitative measurements, see **Figures 1**, **2**), and operating capabilities.

Instrument	total size range (ESD)	Size target for quantitative observations	Typical sample volume	Sampling	Sample	Condition of use	Max. operating range	Method	Approximate cost	Seller	Final results
HIAC	1.3–600 μm	tbe	25–100 ml/min	Water	Fresh (fixed)	On board/ laboratory	na	Optical	26,000 €	Beckman-Coulter	Particles nb, size
Coulter Counter	0.4–1,600 μm	tbe	>8 ml/min	Water	Fresh (fixed)	On board/ laboratory	na	Physical	45,000€	Beckman-Coulter	Particles nb, size
Flowcytometry	0.2–100 μm	0.2–20 μm	10 μL –1 ml	Water	Fixed with Glutaraldehyde	Laboratory	na	Optical	-	several available	Particles nb, type, size
Imaging FlowCytoBot	5–150 μm	10–80 μm	5 ml (15 ml/h)	Water	Fresh (fixed)	*In situ* /on board/ laboratory	40 m	Optical/imaging	$158,000	McLane research laboratories inc.	Particles nb, type, size
CytoSense and CytoSub	0.2–800 μm (optical) 1–800 μm (imaging)	tbe	0.5–5ml (5–1,000 μl/min)	Water	Fresh (fixed)	*In situ* /on board/ laboratory	200 m	Optical (scanning flowcytometry)/ imaging (optional)	90,000–130,000 €depending on configuration	CytoBuoy b. v.	Particles nb, type, size
FlowCam Nano	300 nm–30 μm	tbe	20 μL/min	Water	Fresh / Fixed	On board/ laboratory	na	Imaging	$117,000	Fluid Imaging Technologies	Particles nb, type, size
Flowcam with different objectives: –2X –4X –10X –20X	–75–1,000 μm –20–300 μm –10–100 μm –3–50μm	-tbe –30–100 (water) 200 (net) μm -tbe -tbe	-na 5 ml/min –40 ml 1 ml/min -na 0.2 ml/min -na 0.05 ml/min	Water + Plankton nets	Fresh/Fixed	On board/ laboratory	na	Imaging (triggered by optical signal)	$57,000 $92,500 (laser)	Fluid Imaging Technologies	Particles nb, type, size
Flowcam-macro	300–5,000 μm	tbe	100–900 ml/min (several m3 depending on net cast)	Plankton nets	Fresh / Fixed	On board/ laboratory	na	Imaging	$54,000	Fluid Imaging Technologies	Particles nb, type, size
Zooscan	150–100,000 μm	240– 5,000 μm (depending on nets)	several m3 depending on net cast	Plankton nets	Fresh / Fixed	Laboratory	na	Imaging	26,000€	Hydroptic	Particles nb, type, size
LISST-200	1–500 μm	tbe	-	Cast	Fresh	*In situ*	600 m	Optical	$37,500	Sequoia	Particles nb, size
LISST-Holo2	25–2,500 μm	tbe	30 ml/s	Cast	Fresh	*In situ*	3,000 m	Optical	$39,500	Sequoia	Particles nb, size
UVP-5	60–20,000 μm	60–1,000 μm (optical) 700–10,000 μm (imaging)	100–200 L per 5 m depth intervals	Cast	Fresh	*In situ*	6,000 m	Optical/imaging	92,000 €	Hydroptic	Particles nb, type, size
UVP-6LP	60–20,000 μm	60–1,000 μm (optical) 500–10,000μm (imaging)	-	Cast, gliders, Argo floats	Fresh	*In situ*	6,000 m	Optical/imaging	15,000€	Hydroptic	Particles nb, type, size
ISIIS	60 μm–130 mm	600 μm–130 mm (imaging)	150 L/s at 5 kts	Towed	Fresh	*In situ*	200 m	Focused shadowgraph	$100,000	Bellamare-us.com	Particles nb, type, size

(Continued)

TABLE 1 | Continued

Instrument	total size range (ESD)	Size target for quantitative observations	Typical sample volume	Sampling	Sample	Condition of use	Max. operating range	Method	Approximate cost	Seller	Final results
CPICS	30 μm–20 mm	60 μm - tbe	1 ml (10 ml/s)	Fluids	Fresh/fixed	*In situ*	1,000, 6,000, 10,000 m	Imaging	38,000	CoastalOcean Vision.com	Particles nb, type, size
VPR	30 μm–5 cm	100 μm-tbe	1.25–380 ml (37 ml/s–9.5 L/s)	Water	Fresh	*In situ*	1,000 m	Imaging	$100,000	Seascan Inc. (info@seascaninc.com)	Particles nb, type, size
LOKI	25 μm–2 cm	50 μm–2 cm	1.6–3.5 ml	Towed	Fresh	*In situ*	1,000 or 3,000 m	Imaging	75,000–150,000 €	iSiTEC (sale@isitec.de)	Particles nb, type, size

tbe: to be evaluated.

3.4.2. Imaging Systems

3.4.2.1. Imaging flow cytometry

Imaging flow cytometry (IFC) combines single-particle fluidics, optical characterization and the imaging of cells/colonies. The triggering of an image can be initiated based on different properties of the cell probed ahead of the camera (see Barteneva and Vorobjev, 2015 for a review). Four IFCs have been used routinely within aquatic research, the Imaging FlowCytobot®(Olson and Sosik, 2007; Sosik and Olson, 2007), the Cytosense/Cytobuoy®(Dubelaar et al., 1999), the FlowCam®(Flow Cytometer And Microscope; Sieracki et al., 1998 and the ZooCAM Colas et al., 2018, which differ in their approaches, outputs and size range (**Table 1**).

- The Imaging FlowCytobot records images for all particles above laser scattering and/or Chl *a* fluorescence trigger levels, with consistent image focus enabled by the hydrodynamic focusing principle of the conventional flow cytometric approach of sample injection into a sheath flow (the scattering and fluorescence data are preserved for further analysis). IFCB is a fully automated, submersible instrument with built-in design features (e.g., self-cleaning, onboard analysis of standard beads) that enable long ($>$ 6 months) unattended deployments in the ocean. It is also routinely operated in flow-through systems during ship surveys.
- The CytoSense (and CytoSub which is a submersible version) measures FSC, SSC and multiple fluorescence signals. The scatter/fluorescence scans (pulse shape) show one-dimensional morphology and optical features of big cells, colonies, chains and filaments, converging to "normal" flow cytometry data (totals) for picoplankton. The optional camera makes bright field images of individual particles, hydrodynamically focused along their long axis by low shear acceleration in sheath fluid of particles. At high concentrations of particles which are detected at a fast rate (up to 10 k/s), all particles cannot be imaged and specific values of the optical scans are preselected to act as a trigger. Optical scattering and fluorescence output as well as imaging data are considered as the output of this instrument, while the combination of both properties will increase the classification efficiency.
- The FlowCam uses a similar imaging principle as the Imaging FlowCytoBot (but lacks the hydrodynamic focusing provided by the sheath flow). Images are acquired either continuously (autotrigger mode) or after the detection of a fluorescent (Chl *a*) particle. FlowCam-nano and FlowCam-macro use only the autotrigger mode, respectively, to take pictures of smaller and larger objects and organisms.
- The ZooCAM uses an imaging principle similar to that of FlowCam-Macro.

Notably, depending on the trigger mode of these different IFC instruments, only some of the plankton may be characterized. When fluorescence triggering is used, organisms and particles with undetectable fluorescence will be missed (Reynolds et al., 2010). This does not apply if all organisms and particles are imaged by using scattering signals as an image trigger (e.g., "auto-trigger mode" for FlowCam, "unsupervised mode" for CytoSense).

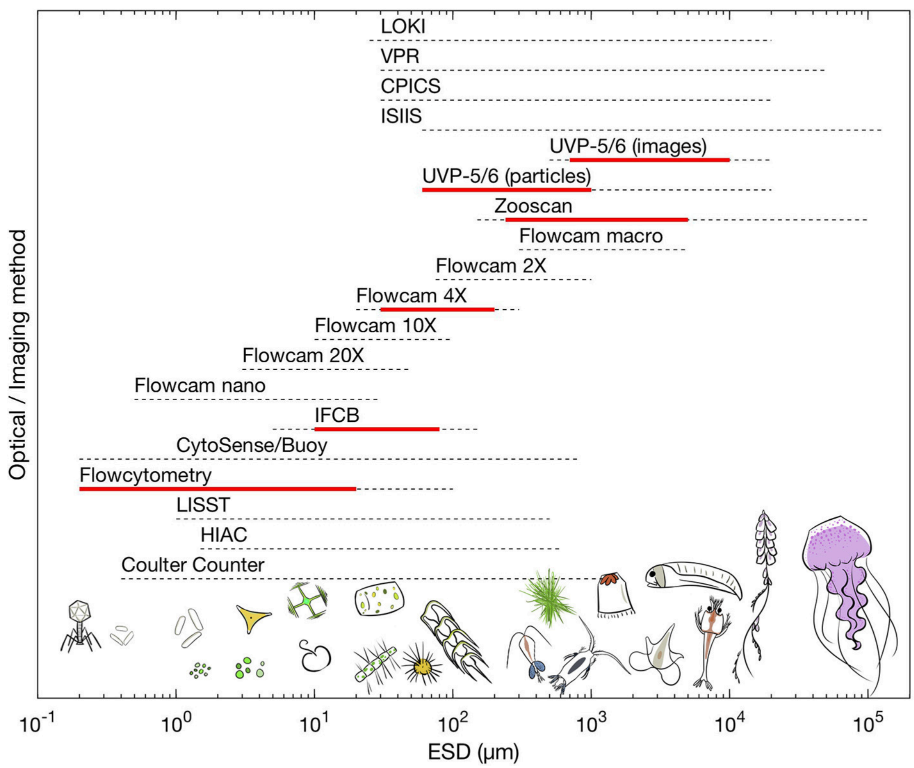

FIGURE 1 | Comparison of the total size range of plankton (in equivalent spherical diameter; ESD) that available optical and imaging methods can sample. Dashed lines represent the total operational size range from commercial information while the red line represent the practical size range which is efficient to obtain quantitative information, for an example see **Figure 2**. Drawings by Justine Courboules.

3.4.2.2. Laboratory and in situ imaging systems

In order to obtain quantitative information on plankton > 100 μm, larger volumes of water need to be examined than is possible with IFCs. *In situ* imaging is non-destructive and can be combined with net sampling. However, there are numerous challenges. The most important criterion is the optimization of the trade-off between sensitivity, resolution, contrast and depth of field so that image quality allows taxonomic identification while the imaged volume is large enough for statistically relevant estimations of concentrations.

High magnification imaging at short distances results in a depth of field (DOF) of only a few millimeters and thus, in a high proportion of out-of-focus images not limited to the DOF (e.g., Schulz, 2013). To avoid motion blurring, short shutter speeds of a few microseconds are required (e.g., Davis et al., 1992; Schulz, 2013). Illumination adapted to the *in situ* and towing conditions should guarantee the image quality and high signal-to-noise ratio of the camera. Imaging systems can be adapted to illuminate a calibrated volume of water for more precise quantification of plankton and particles (Picheral et al., 2010). Due to the above-described trade-offs, *in situ* systems have a relatively restricted size range of operation and focus either on small size classes with a small volume imaged (e.g., CPICS, LOKI), where imaging of sizes less than a few millimeters with a high depth of field is close to the feasible border of the physical laws of optics (Schulz, 2013), or target larger fields of views with less details on organism morphology.

Another method to overcome the *in situ* constrains is to use imaging methods on net-collected plankton samples. In this case the conditions required for an optimal field of view and DOF may be met. However, net tows integrate the plankton over towing distances and can be intrusive, damaging some of the collected organisms. Plankton samples from nets may be imaged either by flow-through chambers (e.g., FlowCam-Macro, LOKI) or plankton scanners such as the ZooScan (Gorsky et al., 2010). Flow-through techniques limit the maximal size of organisms observable to the minimal diameter of its tubing. To avoid clogging, larger individuals are removed prior to analysis. Scanner-based approaches cannot be used *in situ* and are difficult to use at sea. Samples therefore have to be treated with fixatives that can modify the chemical composition of organisms, their color and, in some cases, their morphology. *in situ* imaging provides an alternative to study fragile taxa, such as gelatinous organisms, which may be damaged or destroyed by net tows (Remsen et al., 2004; Stemmann et al., 2008a).

In the following section, a selection of plankton imaging devices (other than the IFCs discussed above) that are commercially available, along with their imaging approach, are briefly introduced (more details are available in **Table 1**). As a general rule, information content on plankton increases with

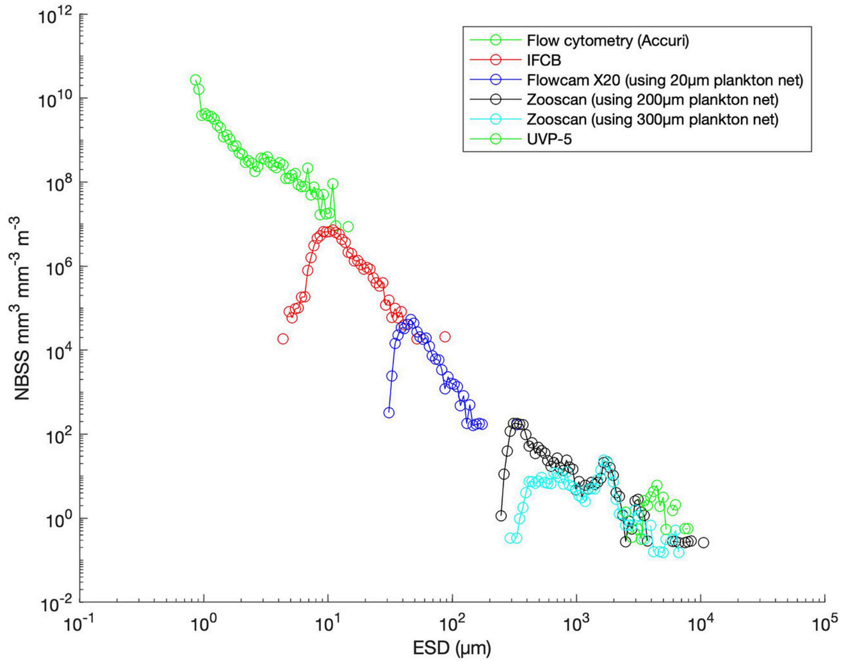

FIGURE 2 | Comparison of total planktonic organisms sampled with different collection methods and analyzed with different optical/imaging methods as a function of the size of organisms (expressed as equivalent spherical diameter; ESD). All sampling was done at the same station during Tara-Ocean Cruise at station 210 (Labrador Sea). Total organism biovolume per size classes were expressed as normalized biovolume size spectra (NBSS) by dividing the total biovolume within a size class by the biovolume interval of the considered size class. NBSS is representative of the number of organisms within a size class. Results were obtained by analyzing whole water with optical method (using an Accuri Flowcytometer) and imaging methods (Imaging FlowCyto Bot-IFCB and Underwater Vision Profiler UVP-5) and plankton net samples of various mesh sizes using imaging methods (Flowcam with a 20X lens and Zooscan). All data are raw counts (removing only objects determined to be not living) and converted to biovolume using elipsoidal calculations. The low count at the smaller size range of each observation corresponds to an underestimation of an object's number due to both limited capabilities of each imaging device for small objects and net undersampling for small objects.

increasing volume and imaging frequency and with decreasing pixel-size. Additional desirable features are that the object be in focus with enhanced contrast and in color. Devices with a pixel size of > 50 μm are designed to study macro-plankton and large aggregates, while those with a pixel size of 5 μm can also resolve micro-plankton.

- The *in situ* Ichthyoplankton Imaging System (ISIIS; Cowen and Guigand, 2008) uses line scan cameras to produce shadowgraph images of plankton. The camera has a field of view of 13 × 13 cm with a depth-of-field of 50 cm and uses a 2,048 × 2,048 pixel sensor, resulting in a 63.5 μm pixel resolution. The system is equipped with environmental sensors, including CTD, fluorometer, dissolved oxygen, and PAR sensors. The volume resolution of the image captures a wide taxonomic range of mesozooplankton and with lower resolution, large protists and cyanobacteria (Luo et al., 2017). The data are transferred to an onboard computer *via* fiber optic in real time while the platform is being towed at 2.5 m s^{-1}, either undulating or at fixed-depth mode to a maximum depth of 150 m.
- The CPICS (Continuous Plankton Imaging and Classification Sensor, Grossmann et al., 2015) is based on a 6 Mpixel color camera and precisely aligned structured illumination to produce a darkfield image with high magnification (between 20X and 0.16X) that images respectively a small volume of seawater (between 2.6 10^{-5} μl and 34 ml depending on magnification) at high frequency [10 frames per second (fps)]. This instrument is deployed *in situ* (on rosette, ROV, AUV, glider or other autonomous vehicle, or buoy) with the possibility for real-time data link to vessel or shore.
- The Video Plankton Recorder II (VPR) is based on dark-field-illumination, operates a 1MPix (10 Bit b/w or color) camera (Davis et al., 2005) and images objects with 25 fps non-invasively and undisturbed in the water column. It images a small volume of seawater (app. 1 ml to 350 ml depending on calibration), and images are sent in real time onboard or shore via a fiber optic tow cable while the Digital Autonomous Video Plankton Recorder (DAVPR) is fully self contained.
- The Underwater Vision Profiler 5 HD (UVP, Picheral et al., 2010) operates a 4 MPix camera imaging a field of view of approximately 180 × 180 mm^2 about 200 mm in front of the camera. The UVP sizes marine snow, aggregates > 100μm and images plankton > 500 μm. It can be integrated on a CTD-Rosette system as a standard sensor delivering images indexed to the different environmental data collected at a rate of 20 images s^{-1}. Its depth range is 6,000 m. The UVP6-LP (low power) is a miniaturized and low power version which is designed to be deployed on ARGO float moorings, AUVs or gliders.

- The Lightframe On-sight Keyspecies Investigation (LOKI) system (Schulz et al., 2010) uses a flow-through chamber with an upstream plankton net. LOKI operates an industrial camera with up to 6 Mpixels at 15 μs shutter time, combined with a tailored high power LED flash unit to image a volume of approximately $20 \times 20 \times 5\ mm^3$ in a flow-through chamber. Images of the LOKI system often allow the identification of fine morphological features as well as discrimination of developmental stages, sex and, in some cases, investigation of internal body structures (e.g., Schmid et al., 2018).
- In recent years two commercial systems have emerged which image particles using holography, which allows for 3-D reconstruction (see Sun et al., 2008) that can image micro-plankton. They take images at very short shutter times, scanning for a relatively large volume. The systems are the LISST-HOLO (now in its $2nd$ version, Sequoia Sci., 4.4 μm pixel size, 1,600 × 1,200 pixel frames, 20 fps) and the HoloSea (4Deep, 1.5 μm pixel size, 2,048 × 2,048 pixel frames, 22 fps). Given their novelty, only a small number of publications have been produced using them or their prototype systems (Bochdansky et al., 2017; Davies and Nepstad, 2017). Automated image reconstruction and recognition requires significant computational power, an issue that is likely to be alleviated in the near future.
- The ZooScan (Gorsky et al., 2010) is a plankton scanner which takes a high-resolution image of net- or bottle-collected plankton samples with a pixel size of 10.6 μm. It has built-in features making it possible to standardize the images of different ZooScans to remote control the image generation and to build a common image databases.

4. REQUIREMENTS FOR PLANKTON OBSERVING SYSTEMS

4.1. A Holistic View of Planktonic Communities

Our current vision of planktonic ecosystems is fragmented largely because of observational constraints. The concentration of organisms decreases with size, and therefore it is practically impossible to sample the full ecosystem, from sub-micrometer to meter-sized colonies of organisms, within a single sampling strategy or with a single methodology (the larger the organism, the larger the volume that needs to be sampled). Second, scientists often focus on a preferred taxonomic or functional range, leading to a kind of taxonomical blindness, with many details for some organisms and very few details for the ones not present in the taxonomical expertise of the specialist. The same is true for models (deYoung et al., 2004). We therefore recommend the adoption of a sustained sampling and analysis plan designed to cover the whole planktonic community, along with characterizing their environment, and incorporate ecosystem modeling in the design (e.g., Karsenti et al., 2011). Few examples of such holistic studies exist (e.g., Waite et al., 2007; D'Alelio et al., 2015; Romagnan et al., 2015). Without such complete sampling of the planktonic community, the quantification of phytoplankton and zooplankton abundance or diversity, which are GOOS EOVs and GCOS ECV, could be biased.

4.2. Interfacing With Modeling Efforts

Marine plankton models are used to address a broad set of issues, ranging from basic science questions including those related to the dynamics of plankton blooms, plankton phenology and species succession (Bopp et al., 2005; Follows et al., 2007; Hashioka et al., 2013; Briseño-Avena et al., 2015; Kuhn et al., 2015), global nitrogen cycling (Jickells et al., 2017; Bianchi et al., 2018), zooplankton vertical migration (Bianchi et al., 2013), the generation of hypoxia (Fennel and Testa, 2019), the quantification of the biological carbon pump (DeVries et al., 2014; Laufkötter et al., 2016), climate change projections (Bopp et al., 2013) and effects of plankton dynamics on ecosystem services related to fisheries (Megrey et al., 2007; Rose et al., 2007; Lefort et al., 2015) to very applied purposes such as the provision of forecasts and reanalyses of oceanic physico-chemical and biogeochemical-relevant variables (see Fennel et al., 2019). However, most current global models represent only limited aspects of the functional diversity of plankton via so-called plankton functional types (Le Quéré et al., 2005) to simulate primary production within the euphotic zone, the transfer of biomass to higher trophic levels, and the pathways of biological carbon sequestration in the deep ocean.

Biogeochemical models typically lack detailed descriptions of zooplankton because of the lack of relevant observations (Buitenhuis et al., 2006), and also because the prevailing paradigm within the modeling community is that global biogeochemical cycles are primarily driven by bottom-up rather than top-down controls. This paradigm is increasingly being refuted by experimental evidence (Lima-Mendez et al., 2015; Guidi et al., 2016) and model studies, which emphasize the important role of zooplankton grazing on nutrient cycling and the biological carbon pump (e.g., Le Quéré et al., 2016), phytoplankton phenology (Hashioka et al., 2013; Ward et al., 2013a) and phytoplankton diversity (Prowe et al., 2012; Vallina et al., 2014). Complex population-structured zooplankton models exist (Hofmann and Ambler, 1988; Carlotti and Wolf, 1998), and models with multiple zooplankton functional groups are increasingly being developed (e.g., Ward, 2018). However, these models have not been widely applied because of the large number of poorly constrained parameters required to describe multiple functional groups and their life stages, physiological traits and ecological interactions (Anderson, 2005; Barton et al., 2013), and because modeling numerous species/stages is computationally expensive. Trait-based modeling frameworks that can simulate an unlimited number of plankton functional types by using allometric relationships between physiological and/or morphological traits (Ward et al., 2012; Ward, 2018) are promising in this regard, but zooplankton functional groups are still underrepresented because of the complexity and heterogeneity of this group, and because the small number of observational data sets available for model development and calibration remains problematic (Carlotti and Poggiale, 2010; Barton et al., 2013; Benedetti et al., 2015; Brun et al., 2016). Most global models now represent up to three size classes of zooplankton, albeit with fixed metabolic rates (e.g., Kishi et al., 2007; Sailley et al., 2013). A further increase in model complexity may be warranted (Benedetti et al., 2018) since taxon- or functional group-specific trophic interactions with phytoplankton and diel vertical migration patterns (Bianchi et al., 2013) may be important to understanding ecosystem dynamics and global biogeochemical cycling (Guidi et al., 2016).

Furthermore, global models generally treat the mesopelagic and deep ocean as a black box because of a lack of ecological understanding of its microbial ecosystems and limited observations (Arístegui et al., 2009). In plankton models, organic matter is routed from phyto- and zooplankton to a few explicit particulate and dissolved detrital pools (Bopp et al., 2013; DeVries et al., 2014; Laufkötter et al., 2016), sometimes accounting for their variable reactivity (Aumont et al., 2017; Bianchi et al., 2018), which then transport particulate organic matter from the surface to the deep ocean via sinking. However, an accurate simulation of nutrient and plankton dynamics in the euphotic zone does not necessarily imply an accurate representation of observed export fluxes (Bagniewski et al., 2011) or consensus on its major pathways within the marine ecosystem (Laufkötter et al., 2016). Marine particle fluxes are known to display strong regional and temporal variability in response to different production regimes and their seasonality, or to the presence of OMZ (Haake et al., 1992; Van Mooy et al., 2002; Guidi et al., 2015), but this variability is not yet well represented in models. Better representations of particle dynamics (Aumont et al., 2017) and particle-plankton interactions may improve simulation of the important mechanisms governing global biogeochemical cycles of carbon and other essential elements, and may thus lead to improved model projections of ocean carbon cycling (Kriest and Evans, 2000; Gehlen et al., 2006), but carbon pathways in models still depend strongly on the data sets used for optimization (Bisson et al., 2018) and the parameterization of their ecosystem modules (Laufkötter et al., 2016).

Robust marine ecosystem/ocean biogeochemistry models that relate climate change to fish production or relating changes in the strength of the biological pump to changes in plankton community structure require an adequate description of phytoplankton, zooplankton and particle compartments in the upper kilometers of the ocean and the mesopelagic, as well as consensus on the major pathways of organic matter transport and transformation, i.e., the fluxes between them. The optimal level of complexity of global models for each biogeochemical or ecological application remains to be determined, and may vary according to the specific target application (Ward et al., 2013b). Therefore, the acquisition of quality-controlled, standardized, global *in situ* data is essential for the development and validation of mechanistic end-to-end models that optimize the balance between fidelity and simplicity for the continuum of the plankton food web, and within the entire water column.

In order to be useful for marine plankton models targeted for biogeochemical and fisheries applications, observation development should provide robust, global information on major taxa (concentration as well as relevant rates), the size distribution of the major plankton groups, as well as the particle size distribution at a biologically relevant spatiotemporal resolution (Capotondi et al., 2019; Fennel et al., 2019). Imaging and other techniques detailed above provide such information even for the deep ocean based on data from *in situ* devices. Yet many observational data sets still lack robust quantification of their uncertainty range, which is essential for model calibration, and some observations are still of limited use for model applications due to the lack of a common set of comparable standard products. A close collaboration between modelers and experimentalists can guarantee the usefulness of data products for this important user group, and thus a better quantification of the present and future biogeochemical functioning of the ocean and health of its ecosystem (Siegel et al., 2014).

4.3. Achieving a Globally Consistent and Holistic Plankton Observing System:

Given the TRL of the technologies for the observation of plankton biomass and diversity reviewed above, these types of technologies are ready to be included in a global observation network (Miloslavich et al., 2018).

As a first step, integration of plankton measurements into existing global observing systems (e.g., GO-SHIP Sloyan et al., 2019, OCEAN-SITES, BGC-ARGO Roemmich et al., 2019) could serve as the vehicle to ensure wider integration in the future. Observing systems are international and distributed (i.e., do not depend on a single nation), therefore requiring a high level of international coordination and standardization. Such efforts could have a direct benefit for smaller scale observing systems if the lessons learned and data infrastructure were shared with them.

Ocean sites where time series observations are conducted (Benway et al., 2019) provide natural foci for experimental process studies. If possible, observational technologies should be augmented with measurements of functional interactions and rate processes (e.g., primary and net community production, growth and grazing rates, predator-prey interactions, export fluxes) since understanding such processes is critical to linking ocean observations with functional models of biogeochemistry and ocean food webs.

The observations should follow basic procedures in order to guarantee the best comparable outputs for present and future studies:

1. Methods should be standardized across the whole observing system and should be validated outside of the lab which developed them. Where necessary, protocols of best practice should be produced and made widely available (e.g., OceanBestPractices, 2018). Standards for each measurement should be defined so that all related measurements can be quantitatively compared with respect to the standard. Standardization of methods should include standardizing the methodology for quality control and of data curation.
2. Plankton samples should be associated with environmental variables acquired simultaneously (e.g., from remote and local sensors). More information about the environment as well as the plankton (e.g., using different sensing and sampling

methodologies) will lead to deeper understanding of the plankton and their relation to the environment.

3. Sampling should include as complete a spectrum of plankton as possible, spanning size and function, across a variety of places, depths and times. De-correlation scales in time and space should be taken into consideration to maximize the use of resources. Sustainable observations at specific locations and along transects enable the quantification of temporal trends.
4. Methods should be cross-compared (*e.g.,* nets, CPR, imaging systems) and inter-calibrated to ensure that uncertainties and potential bias are known. When using proxies for particles and plankton properties (e.g., bio-optics and bio-acoustics), periodic ground-truth ensures biases are constrained. Measurements of related/complementary variables (e.g., pigment concentration, POC and phytoplankton volume from FCMs and IFCs of surface samples, bio-acoustic and quantitative imaging) can be used to point out anomalous data for flagging if the different measurements are not consistent with established relationships.
5. Protocols for adopting new technology should be in place (e.g., how long should there be side-by-side deployment and inter-comparison before replacement of old with new). These documents should identify the advantages and limitations of the measurements to provide realistic quantified uncertainties. There are a few existing inter-comparisons between existing sampling devices (notably between nets, e.g., Stehle et al., 2007 and references therein) which have been conducted, with few exceptions, years after the introduction of the new technology. Similarly, imaging techniques have seldom been inter-compared and calibrated with field-specific standards (e.g., Colas et al., 2018), and the inter-comparison has often taken place long after the introduction of a new device (e.g., Schultes and Lopes, 2009; Reynolds et al., 2010; García-Comas et al., 2011; Forest et al., 2012; Thyssen et al., 2014; Le Bourg et al., 2015).
6. Because of the potential improvement of techniques and changes in scientific interests, it is very important that physical plankton samples obtained with nets or water samples be properly archived for future reanalysis. Similarly, as image analysis methods improve, images (or optical properties) could be reanalyzed at later dates.

5. CHALLENGES

5.1. Deciding on What to Measure With a Finite Budget

There is a need to develop a strategy regarding the methods and measurements to be done. Prioritization should be based on: (1) cost (e.g., human capital needed, cost of analysis and/or instrument, ability to take advantage of existing already-funded efforts), (2) central variables in the context of global ecosystems (EOVs) and biogeochemical processes and (3) associated ecological information content. Emphasis should be placed on a holistic sampling program with sufficient redundancy to ensure success and reduce uncertainties. It follows that scientists versed in modeling, observations, data mining and marine resource management should be consulted to optimize this strategy, which will likely involve both *in situ* observations as well as samples for laboratory analysis.

5.2. Sampling Design and Constraints

Counting statistics indicate that, to treat a population as continuous, about 400 individual particles need to be enumerated in the volume analyzed (Siegel, 1998). This requirement means that while the distribution of bacteria can be assessed with samples as small as a milliliter, to sample macro-zooplankton, hundreds of liters may be necessary. Spatial heterogeneity further increases the number of required samples. This constraint also means that the sampling volume will increase dramatically with the desire to obtain more resolved taxonomic information, particularly for larger organisms. Plankton nets provide means to sample large volumes (and hence large number of individuals) while selecting for specific groups that are well sampled within nets and integrating vertical and horizontal gradients. Imaging systems, while better suited for targeted spatial sampling and fragile organisms, need to be deployed in such a way as to obtain sufficient numbers of individuals and to minimize avoidance of *in situ* instruments by the targeted organisms (e.g., minimal physical perturbation to the environment, appropriate lighting to avoid biasing observations especially at night or at deep depth).

5.3. Managing and Integrating the Massive Data Flow Originating From a Network of Different Instruments

An integrated observation system will be useful and relevant only if the data collected are available and meet user needs. Data dissemination platforms should comply with common standards of Findability, Accessibility, Interoperability, and Reusability (FAIR; Wilkinson et al., 2016). At the moment plankton-relevant oceanographic data are scattered within different databases (e.g., OBIS, COPEPOD, PANGAEA, IGMETS, SeaBASS, BCO-DMO, EMODNET), which are data repositories of variable ease of use. Each of these data portals offers only a partial view of the ecosystem, focusing on very specific features (e.g., species presence for OBIS, zoo- and phyto-plankton biomass for COPEPOD, pigments and optical parameters in SeaBASS) and often lacking links to contextual data originating from the same sampling event or cruise. For a modeler interested in constructing a holistic view of the ecosystem during a particular field effort, they have to invest significant effort to find and access to relevant data in all the different repositories. Linking between them could significantly facilitate more complete exploitation of the data (Benway et al., 2019; Tanhua et al., 2019b). Indeed, OBIS has recently adopted the Event Core format of Darwin Core and developed the Extended Measurement or Fact Extension, enabling linking sampling facts including environmental measurements to an event hierarchy and biotic measurements (e.g., biomass, absence/presence, fatty acids, pigments) to the occurrence records (De Pooter et al., 2017). Another important limitation is the lack of uncertainties associated with the data in most data repositories as well as the lack of defined quality control annotations. Hence, the users are often left with the need to develop their own uncertainty estimates, for example to propagate in their calculations or to test model sensitivity. Beyond the necessity to integrate the data sets, users of such databases should be regularly consulted to ensure they are fit for purpose.

5.4. Curating, Validating and Distributing Imaging Data

Imaging systems deployed for oceanographic research worldwide already collect millions of images a year. Large-scale infrastructure is therefore needed to host and distribute this wealth of data. Such infrastructure should provide a collaborative way to visualize and classify images, perform quality control on these identifications, and share the resulting data in an open-access manner.

A prototype infrastructure for quantitative imaging datasets (EcoTaxa) has been developed. EcoTaxa is a web application (http://ecotaxa.obs-vlfr.fr) that allows users to store images of individual organisms and associated metadata in its database, efficiently classify these objects within a universal taxonomic reference, and export the resulting data for further analyses. It uses machine learning, combining classical approaches and Convolutional Neural Networks in a user-friendly way, to help ecologists, even those with no computer-science background, classify large numbers of images (typically >10,000/operator/day). It is meant to be collaborative, allowing an unlimited number of users to interact on the same dataset (all using the same taxonomic tree). Their work can be iterative (by correcting each other's mistakes) while always retaining the full history of identification for each object, and machine learning models can be built based on all classified images in the database.

Currently (as of Jan 25th 2019), EcoTaxa hosts >72 million images of plankton (42% of which have had their identification validated by a human operator), collected with more than seven different instruments, over the world's oceans. In 3 years, it attracted ∼550 registered users from ∼160 institutions. While functional, this prototype needs to be deployed more widely, on servers backed by academic institutions, and improved in various ways. For example, the database may not perform as well with billions rather than the current millions of images. The taxonomic back-end will benefit from the unification of phylogenies allowed by nucleic acid sequencing (e.g., https://unieuk.org). Finally, the machine learning back-end should benefit from various ongoing efforts to infuse more computer science knowledge into ocean sciences. The available database of images has already proved to be a good tool to foster such initiatives by providing a wealth of classified data (Elineau et al., 2018). Efforts are partly funded and underway to address the limitations outlined above.

EcoTaxa also includes a 'Particle module' (http://ecotaxa.obs-vlfr.fr/part/) intended to store, visualize, and export data originating from *in situ* instruments that quantify marine snow (UVP, LISST, LOPC). In this application, all data originating from the same sampling event (CTD data, marine snow abundance, and plankton identified from images) are gathered in the same dataset and can be downloaded by visitors. Data from any device counting and measuring particles can be easily integrated into this module.

5.5. Near Real-Time Data Processing

For certain applications (e.g., adaptive sampling of deployed assets), near-real-time data processing and quality control is critical. Much effort has been invested in BGC-Argo to process the biogeochemical data in near-real-time (including flagging data that are likely problematic, Roemmich et al., 2019). Similar efforts have also been invested on developing such strategies for fixed infrastructures (e.g., IOOS, 2018). Global coordination of such efforts and the addition into them of more plankton-relevant parameters will ensure optimal use of these data (e.g., Tanhua et al., 2019a). In addition, delayed-mode processing is often needed for plankton variables (e.g., once water samples needed to calibrate proxies are available).

5.6. Enhancing Capacity and Knowledge

The community with the knowledge necessary to collect, quality control, analyze and interpret plankton data is small, and the current assets to sample the world's oceans are extremely limited given the task at hand (to monitor the distribution of plankton-relevant variables in time and space throughout the world's oceans). In addition, taxonomic expertise has declined, which severely limits many types of investigations. Significant efforts in education, collaboration (sharing of expertise, computer codes, instruments, annotated image databases, etc.) and invention of sensors to be deployed for longer periods of time on autonomous platforms can help mitigate this limitation. In addition, the creation and adoption of best practices can be an important element in training to increase the uniformity and interoperability of measurements (Pearlman et al., 2018). Finally, plankton ecology needs to develop further to take full advantage of the measurements collected.

5.7. Maximizing Return on Investment

To ensure sustained and continuing investment in plankton monitoring, it is critical to enlarge the community of active users of such data. An approach could include the generation of simple indicators summarizing the complex ecological data (simple and user friendly but not simplistic) and will require the education of users through virtual tools, workshops, summer schools, and capacity building to include potential user communities and stakeholders (e.g., from modeling, resource management, environmental agencies and private companies).

6. RECOMMENDATIONS ON HOW TO PROCEED DURING THE NEXT TEN YEARS

Building a global observation system to describe planktonic key variables and predict the functioning of the pelagic ecosystems requires a stepwise approach with regional-scale experiments as pilot projects while engaging with existing global programs and infrastructures to increase their sampling capacity. Such pilot studies, combining *in situ* sensors deployed on long-endurance platforms with satellite sensors, ship cruises and in conjunction with data-assimilating biogeochemical-ecological models, will provide a scalable template from which to grow and improve upon. Acquisition of biological variables should be performed in a consistent framework to facilitate inter-comparison between methods and projects. To ensure quality of data, adherence to agreed upon best practice protocols, including specific actions such as inter-calibration, is necessary. We suggest that the following itemized strategies should be used to prioritize investments and provide below each some example activities (some may contribute to more than one priority):

6.1. Priority I: Make the Best of Existing Data, Share Publicly, Inter-calibrate/inter-compare Existing Observations and Technologies, Work on Common Protocols, Improve Accessibility of Existing Databases and Searchability of Data at Multiple Levels of Organization

Promote free data and information sharing by using open access publication strategies of both articles and source data and following a "FAIR" principle (Wilkinson et al., 2016). Build robust distributed networks for collection, distribution and curation of data (like Argo and EcoTaxa) that do not depend on one country's funding and that serve the full scientific community worldwide (see Tanhua et al., 2019b). Channel the data to global and consistent public databases such as OBIS or other existing platforms in consultation with modelers. Make sure funding agencies that require data curation from funded PIs are consulted and in agreement with adopted approach.

Ensure there are experts available to assist the larger community with quality assessment and control (QA/QC) of plankton-relevant data collected by non-specialists. For imaging in particular, ensure there is ready access to taxonomic information/expertise, and find ways to reward people who serve the community (e.g., encourage data publication with citable DOI for databases). Make lists and databases of taxa at different organization levels (for example, one with 5 taxa that are well identified and one with few tens of taxa when automatic sorting is followed by detailed human annotation).

Work on best practice documents to ensure worldwide methodology is consistent (Pearlman et al., 2018) and inter-comparable. Encourage the contributions of documented best practices to a global scale repository to facilitate consensus and adaption of common methodologies.

6.2. Priority II: Generate Novel Data in a Reasonable Way, i.e., Using Common Global Standards for Data Generation, Taxonomic Identification, Quantification of Uncertainty, Comparing Against Standards

Invest in efforts to homogenize plankton-relevant variables between national and international programs, and to inter-compare and inter-calibrate methods to ensure measurements can be integrated into a global observing system and modeling framework.

Invest in the integration of tried-and-true technologies for plankton measurements on globally coordinated programs collecting time-series and transects which currently do not measure these systematically (Weller et al., 2019). Proceed with this integration incrementally - e.g., start with one GO-SHIP line that is occupied annually and use it as an example, and as the basis for writing the appropriate protocols and the expansion to other transects and cruises. Invest in the integration of mature and calibrated sensors to AUVs to expand coverage in space and time. Take into account in planning that the synergistic value of collocated measurements, providing significantly more information than the sum of the individual measurements.

6.3. Priority III: Think About Collaboration, Co-funding and Joint Projects Between Different User Groups

Closely interact with modelers to derive and produce outputs/indices relevant to the models. Organize workshops with modelers to explain the added value of the new measurements, and interact closely with modelers to identify their needs (e.g., to ensure measurements target what models are sensitive to) and make them aware of observation efforts. Apply for co-funding for experimental and modeling studies to encourage co-involvement of both fields in the initial planning and final use of the results (e.g., Tara expeditions).

Organize summer schools and workshops, dedicated to students, early career scientists, senior scientists, but also stakeholders and policy makers, to ensure transfer of theoretical (plankton ecology, diversity and taxonomy) and technical knowledge, consistency in processing (e.g., image annotation), dissemination, and increased use of data collected. Document the material provided through the summer school in a repository (e.g., videos of classes, PDFs of materials, etc.) to support long-term opportunities for training.

Promote the exchange of expertise between northern and southern hemisphere countries by disseminating the existing expertise on plankton imaging/optical measurements to scientists and students from less-developed countries, particularly in the southern hemisphere, where the largest gaps in our knowledge still persist, but where sometimes taxonomic expertise is still strong when it has been progressively lost in northern countries.

6.4. Priority IV: Innovate and Develop New and Better Technologies for the Development of Augmented Observations

Keep innovating! Keep investing in the development of new sensor/sensing, of new analytic tools and pipelines on the use of automated optical/imaging techniques for building new biodiversity indicators.

Take advantage of developments from other fields (e.g., computer science, optical engineering, etc.) to improve our current sensing systems. Look for opportunities to reduce the costs of measurements without decreasing their quality (e.g., Wang et al., 2019), in such a way that future equipment could be embarked with as standard tools on cruises and/or autonomous platforms (floats, gliders).

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FL and EB coordinated and contributed equally to the writing of the manuscript. AMW, MV, JU, LS, HMS, JS, J-BR, MP, JP, MDO, BN, KOM, PM, AL-L, RKi, RML, RKu, LK-B, JSJ, MHI, J-OI, HH, LG, GG, SLG, PG, SG, KF, GD, RKC, FC, CB-A, LB, KB-B, NB, SB, SDA, LFA, and WA provided input on the full manuscript.

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frontiers in Marine Science

MINI REVIEW
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Frontiers in Fine-Scale *in situ* Studies: Opportunities During the SWOT Fast Sampling Phase

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Conceived as a major new tool for climate studies, the Surface Water and Ocean Topography (SWOT) satellite mission will launch in late 2021 and will retrieve the dynamics of the oceans upper layer at an unprecedented resolution of a few kilometers. During the calibration and validation (CalVal) phase in 2022, the satellite will be in a 1-day-repeat fast sampling orbit with enhanced temporal resolution, sacrificing the spatial coverage. This is an ideal opportunity – unique for many years to come – to coordinate *in situ* experiments during the same period for a focused study of fine scale dynamics and their broader roles in the Earth system. Key questions to be addressed include the role of fine scales on the ocean energy budget, the connection between their surface and internal dynamics, their impact on plankton diversity, and their biophysical dynamics at the ice margin.

Keywords: remote sensing, ocean dynamics, energy cascade, biogeochemial processes, submesoscale, mesoscale

INTRODUCTION

Importance of Fine Scales

The oceanic fine scales (1–100 km) have relatively short time scales but crucially affect ocean physics and ecology up to the climate scale, due to the strong gradients created by energetic dynamics (Ferrari and Wunsch, 2009; Su et al., 2018). These gradients are associated with strong vertical transport, connecting the ocean's upper layer to its interior (Lévy et al., 2001; Ferrari, 2011). The horizontal and vertical fine-scale dynamics modulate the energy cascade (McWilliams, 2016) as well as ice-sea (Manucharyan and Thompson, 2017) and air-sea (Lehahn et al., 2014; Sasaki et al., 2014; Renault et al., 2018) interactions. The temporal scale associated with these horizontal and vertical fine scales is days to weeks, the same as in many important ecological processes including phytoplankton demography and competition, and the duration of foraging trips for many marine predators. This temporal resonance is one of the reasons behind the fine-scale variability that appears in marine ecosystems and their services, including biogeochemical cycles (Lévy et al., 2012; Olita et al., 2013; McGillicuddy, 2014; d'Ovidio et al., 2015; Mahadevan, 2016; Lehahn et al., 2018), biodiversity (d'Ovidio et al., 2010; Lévy et al., 2015), fish distribution (Godø et al., 2012; Watson et al., 2018), and even foraging strategies of megafauna (Tew Kai et al., 2009; Della Penna et al., 2017).

A Troubling Gap at the Global Scale Between Fine-Scale Modeling and Observing Capacities

On the modeling side, great progress has been made in characterizing this regime over the past few decades. Physical and biophysical configurations for processes of the order of 10 s of km are now considered standard for regional circulation models. Field campaigns like AlborEx (Pascual et al., 2017), LatMix (Shcherbina et al., 2015), LATEX (Petrenko et al., 2017) have also shown that individual fine-scale features may be experimentally targeted. The frontier now stands in the integrated role of the fine scales in the Earth system: what are their net global impacts? How do their properties vary regionally and seasonally? On this topic a troubling gap has formed between models and observations. Field campaigns can target individual features, but they represent a tiny fraction of the possible ocean conditions. Moreover, most *in situ* studies are biased by the choice of stronger and longer-lived fine scales, which are the only ones that can be reliably tracked today with remote sensing tools. We rely on models extending these observations to the global ocean (e.g., Qiu et al., 2018), but this knowledge gap between models and observations at the global scale may hide key physical or biophysical mechanisms that models do not represent correctly.

The Role of Remote Sensing and the SWOT Mission

In order to address this knowledge gap, the scientific community has been focusing on novel platforms. Among these are satellite missions that will provide global coverage at high spatiotemporal resolutions. Remote sensing does not provide ground truth of all fine-scale physical and biophysical processes, but can provide a critical synoptic context for fine-scale features, helping to separate spatial from temporal variability, supporting strategies for *in situ* field campaigns, and assessing the representativeness of *in situ* data. A future fine-scale resolving satellite mission is the NASA/CNES SWOT (Surface Water and Ocean Topography) satellite mission, to be launched at the end of 2021 (see details in the Morrow et al., 2019 SWOT paper in this same issue). SWOT is an altimetric mission. While satellite altimetry today provides one-dimensional, along-track observations, SWOT will provide wide-swath, two-dimensional sea surface height (SSH) fields similar to sea surface temperature (SST) and ocean color fields, but without being affected by clouds, due to its microwave Ka-band radar interferometer. SWOT will directly provide a key dynamic variable of the ocean, SSH, with a 2D view at an unprecedented resolution (15–30 km in wavelength, depending on sea state: see Morrow et al., 2019 for details).

Two Phases, One Unprecedented Opportunity

The SWOT mission is characterized by two temporal phases. The first phase is for mission calibration and validation. It will last 3 months (January–March 2022) with a 1-day-repeat cycle (so-called "fast-sampling phase"). The second phase (so-called "nominal orbit") will have a 21-day-repeat cycle and last several years (Morrow et al., unpublished). Here we focus on the unprecedented experimental opportunities offered by the fast-sampling phase in early 2022. These cloud-free SSH observations are available across large regions (120 km wide swaths and their crossing point, so-called "crossovers," see **Figure 1**). These are distributed all around the globe, with a temporal resolution of 1 day. This 1-day repeat has never been available with the conventional nadir-looking altimetry in the past and is not expected from other planned missions in the future. In the following we present some of the observational opportunities for which SWOT is expected to be especially useful, as well as challenges and recommended practices for interpreting its maps. Examples of *in situ* campaigns that are planned under SWOT crossovers are then described.

SCIENCE OPPORTUNITIES FOR PHYSICAL AND BIOPHYSICAL PROCESSES

Studying the energy budget in the ocean requires fine-scale observations. The dynamics of fine scales plays a key role in both the direct and inverse energy cascade (McWilliams, 2016) and therefore in the regulation of the ocean energy budget. Fine scales are associated with potential energy to kinetic energy conversion in high wavenumbers (Boccaletti et al., 2007) and eventually kinetic energy dissipation (Nikurashin et al., 2012). A precise spatial and temporal representation of these processes is required for a correct estimation of the ocean energy budget and for designing optimal parameterizations for high resolution, as well as climate resolving numerical models. For example, the intensity of the fine-scale density gradients and vertical velocities in numerical models strongly depends on the rate of kinetic energy accumulation along the direct cascade, before being dissipated by microscale non-linear processes.

Today, there are no direct fine-scale observations of ocean currents from space. Surface geostrophic currents derived from satellite altimetry maps only represent large scales >150–200 km (Chelton et al., 2011) which are mostly in quasi-geostrophic balance. At spatial scales smaller than 200 km, geostrophic or cyclo-geostrophic motions are not always dominant. SWOT SSH will observe both balanced (eddies) and unbalanced (internal tides and internal gravity waves) motions at these scales. This is

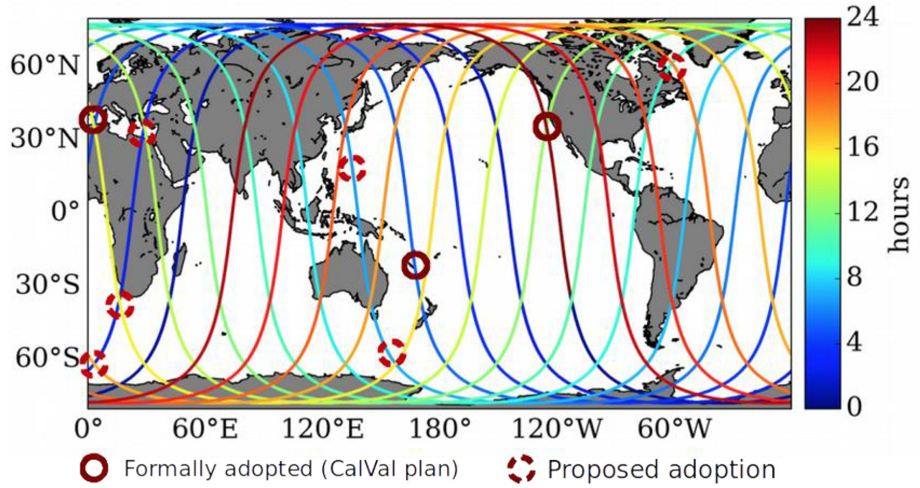

FIGURE 1 | SWOT orbit during the fast-sampling phase [adapted from Wang et al., 2018, ©Copyright (2017) AMS]. During the first months of the mission (expected for January–March 2022), the satellite will be on a special orbit which will overfly a smaller portion of the global ocean with a repeat cycle of 1 day (twice per day on crossovers). This so-called fast-sampling phase will resolve both the spatial and the temporal variability of the ocean fine-scale features along the ∼120 km wide swath. Successively, the nominal orbit of SWOT will cover the entire globe (between 78 N and 78 S) with a repeat cycle of 21 days. The circles represent the study regions discussed in Section "Some Case Studies for the SWOT Fast-Sampling Phase."

an opportunity to characterize their 2D spatial structure globally, and to observe their interactions, important for the ocean energy budget, mixing and dissipation.

Biophysical couplings at fine scales present large uncertainties, introducing a notorious main source of error in representing ocean dynamics on a variety of interdisciplinary issues, ranging from the biological carbon pump and its associated export (Lévy et al., 2012; Siegel et al., 2016) to plankton diversity and spatial planning of commercial fisheries (Scales et al., 2018; Watson et al., 2018) and marine protected areas (Della Penna et al., 2017). The observations during the SWOT fast-sampling phase present a novel opportunity for studying the ecology of microbial populations, in particular when paired with high throughput techniques. Characterization of the microbial community structure by morphological techniques [automated flow cytometry Marrec et al. (2018)] and machine learning applied to microscopy as well as "-omics" techniques (e.g., Villar et al., 2015) are underway and now provide the possibility of repeatedly mapping the fine-scale planktonic community structure and dynamics on regions spanning several tens of km in a quasi-synoptic way. When deployed on the regions overflown by SWOT during the fast-sampling phase, these techniques should yield empirical evidence of the ecological effect of impulsive events tied to fine-scale physics (Talmy et al., 2014).

Finally, SWOT data during both the fast-sampling and nominal phases have a high potential for marine ecology applications. Animal telemetry studies have shown to greatly benefit from the comparison with altimetry-derived circulation features (e.g., Della Penna et al., 2017). These biologging data are the cornerstone for the spatial planning of marine protected areas. However, biologging fine-scale resolving precision, which is now routinely available, remains largely unexploited due to resolution limitations in nadir altimetry gridded products.

CHALLENGES FOR COMBINING SWOT AND IN SITU OBSERVATIONS

Entanglement of Space and Time Variability

In most cases, a detailed understanding of the fine-scale processes associated with SSH fine-scale physical features will not be possible on the basis of satellite information alone but will require *in situ* information as well. In this regard, a fine-*scale in situ* observing network optimized for SWOT observations should ideally instrument a region ∼100 km × 100 km wide, with a ∼km horizontal spatial resolution and ideally hydrographic profiles extended up to the bottom. The key challenge, however, is the time constraint. The daily or shorter temporal resolution required to disentangle fine-scale spatial and temporal variability, currently renders a regular mapping which respects all these requirements out of the reach. The definition of a fine-scale sampling strategy is therefore a critical task which consists of choosing which aspects to favor and which to sacrifice (Wang et al., 2019). Viable solutions (Shcherbina et al., 2015; Jaffe et al., 2017; Pascual et al., 2017; Petrenko et al., 2017; Wang et al., 2018; see also section "Some Case Studies for the SWOT Fast-Sampling Phase") include the use of an affordable number of moorings deployed on a smaller area, or along a one-dimensional array; the restriction to ship-based shallow CTD casts and to instruments in use, to minimize the occupation time at sample stations; the coordinated use of autonomous platforms; and the use of non-regular, time-dependent (i.e., adaptive) grids. All these strategies may benefit from near-real time feature detection (e.g., d'Ovidio et al., 2015) from satellite and *in situ* data, in order to optimize the position and orientation of the sampling grid.

Entanglement of the Balanced and Unbalanced Motion

At spatial scales <200 km, the combined observation of balanced (eddies) and unbalanced motions (internal gravity waves and internal tides) impose great challenges in interpreting and fully utilizing the high-resolution SWOT SSH data (Qiu et al., 2018). In contrast to the majority of the larger SSH features observed with nadir altimetry, not all the SSH fine-scale gradients correspond to quasi-geostrophic currents. Recommended approaches for disentangling the two components exist and need to be implemented in order to avoid errors in the interpretation of SWOT observations. First of all, the regional and seasonal variation should be considered, as the relative strength of balanced and unbalanced motion greatly varies in space and time (Torres et al., 2018). The transition scale from balanced to unbalanced motion, as well the seasonal variations of their relative strength have been documented with good accuracy from both model studies and *in situ* observations (Qiu et al., 2017). These data can provide valuable *a priori* information to disentangle balanced and unbalanced motion. Internal tides contribute a significant SSH signature at scales <200 km, and coherent internal tide corrections are being developed to remove tides from future fine-scale altimetry and *in situ* data (e.g., Zaron and Ray, 2017). In addition, *in situ* ADCP or glider measurements will also help the eddy-wave separation following the framework provided in Rainville et al. (2013).

SOME CASE STUDIES FOR THE SWOT FAST-SAMPLING PHASE

The primary objective of the fast-sampling phase is mission CalVal. During this period, orbit crossovers will open opportunities for challenging *in situ* data with several processes, which until now, mainly addressed model studies (like the ones described in section "Science Opportunities for Physical and Biophysical Processes") on a variety of ocean regions. These opportunities are unique in providing synoptic images of the fine-scale ocean circulation twice a day. The SWOT nominal period for the fast-sampling phase is January–March 2022. With an acknowledgment of the risk of the mission being postponed due to unplanned technical delays, the SWOT Science Team encourages the international community to coordinate future fine-scale campaigns around the world so that a large number of SWOT crossovers will be occupied by *in situ* studies during the fast-sampling phase. Besides the principal CalVal site in the California Current System (Wang et al., 2018; Morrow et al., unpublished), we present here some other possible locations (**Figure 1**) and the associated planned *in situ* activities at various levels of maturity.

The Western Pacific: Energetic Mid-Latitude Sites and Tropical Regions With Internal Tides

The Subtropical Countercurrents in the Western Pacific is baroclinically unstable, producing energetic eddies. In this region, the Pilot National Laboratory for Marine Science and Technology (Qingdao) is planning an *in situ* observing system along the SWOT ground track as part of its Ocean Energy Cascading Observation Study, aiming to validate and complement the SWOT measurements. Three moorings will be deployed in a triangular shape separated by ∼20 km. They will collect hydrographic records over the upper 3000 m to calculate dynamic height and infer SSH and velocity records above the main thermocline (∼500 m). With sufficient funding support, this mooring system could be extended over a larger spatial domain by deploying additional moorings or gliders as substitutes. The collected data should provide a benchmark for validating the SWOT-measured SSH and the inversion of three-dimensional ocean flows based on SSH. Within the triangular mooring system, additional underwater and wave gliders are planned to resolve processes toward the submesoscale (∼3 km).

In the region around New Caledonia in the South-West Tropical Pacific, where strong internal tides are observed, another study is planned in the framework of the SWOT CalVal plan. Deployments of moorings, gliders, and ship-borne studies using underway CTDs and AD will be used to understand and characterize the interactions between high frequency motions and mesoscale activity.

Polar and Subpolar Regions

The Antarctic Circumpolar Current

The Southern Ocean is a major player in the heat (Liu et al., 2018) and carbon (DeVries et al., 2017) uptake and transport, with the Antarctic Circumpolar Current (ACC) being the strongest current in the world, with hotspots occurring where the current interacts with topographic features (e.g., Chapman and Morrow, 2014). In recent years, studies have pointed to fine-scale processes that are able to dominate biogeochemical transfers (e.g., Swart et al., 2015). During the 1-day repeat phase, one SWOT track will cross the ACC upstream from Macquarie Ridge, a highly energetic ocean environment. This region has a high signal-to-noise ratio in SWOT measurements compared to adjacent ACC areas (Wang et al., 2019). It is of great interest, with expected sub-mesoscale signals in the form of internal waves, sub-mesoscale eddies and other potential small-scale features while crossing some sharp fronts of the ACC. The daily-repeat SWOT measurement allows the detection of the coherence of features and their connection to *in situ* observations (ship-based, floats, moorings, drifters, gliders). A pre-SWOT cruise (October 2018) in the area led by IMAS/CSIRO/ACE-CRC will be the base prototype of an *in situ* effort to be proposed in 2022 during the SWOT fast sampling phase.

Another Southern Ocean crossover is located in the Cape Basin. Interactions between the Agulhas Current Retroflection, its associated shedding of large (order of 200 km) Agulhas Rings, circulation of the Benguela Upwelling Region/ Benguela Drift, and the northern domains of the ACC, provide a truly complex "cauldron" of oceanic flows (Dencausse et al., 2011) that have climate-relevant impacts at both regional and global scales. Large thermohaline horizontal gradients, strong shear flows and intense atmosphere-ocean exchanges (Rouault and Lutjeharms, 2000) are associated with these interactions and can fuel baroclinic instabilities that evolve rapidly and at a small scale. The protrusion of the edge of the Agulhas Bank and other bathymetric features (Agulhas Ridge, the Protea, Simpson, Wyandot, Schmit-Ott seamounts) allows for an energy exchange between a very active meso- to submesoscale flow field (Dencausse et al., 2011; Kersalé et al., 2018) and underlying topography, causing further instabilities and variability. SWOT information can be contextualized with past or ongoing observational efforts in the region (the eastern SAMBA tall moorings PIES and Argo vertical profiles, glider deployments, and monitoring lines, – Du Plessis et al., 2017; Krug et al., 2017; Kersalé et al., 2018). Logistically, the relative proximity of Cape Town, research ships and existing facilities, provide reasonable access to the site to conduct ship-based surveys and deployments of high-resolution sampling platforms such as profiling gliders and autonomous surface vehicles.

Sea-Ice Dynamics and Subpolar Seas

Other opportunities for both hemispheres come from the potential use of SWOT observations to study the interactions of the cryosphere (the ice shelves, the icebergs and the sea ice) with the open ocean. The structures are commonly observed from satellite images of sea ice but are not, or are poorly observed by available altimetry satellites due to orbit limitations, a coarse resolution or the proximity of coastlines – all issues that will be addressed by the SWOT mission. For example, Manucharyan and Thompson (2017) recently showed with a model study that eddies and filaments form in the Marginal Ice Zone (MIZ) at the time of sea ice melt, due to baroclinic instabilities caused by salinity and temperature gradients. These features persist for several days and induce large oceanic vertical velocities (10 m d^{-1}). In addition, fine-scale physical information ought to be linked to the recent discovery of sea ice fall in algal bloom that can directly be observed from satellites (Lieser et al., 2015). The interactions between ice shelves and the ocean are also prone to form ocean mesoscale eddies at the front of ice shelves (Li et al., 2017). These "shelf-eddies" might play an important role in the transfer of heat toward the ice shelves, and on the biogeochemistry of the coastal Southern Ocean. In the Southern Hemisphere, there are several SWOT crossovers which will fall over the Antarctic ice margin zone and over the Antarctic shelf break, which therefore are good candidates for the aforementioned problems. In the Northern Hemisphere, one of the SWOT ground tracks crosses a series of hydrographic sections located in the Labrador Sea, a biologically rich sub-arctic sea regularly monitored by Fisheries and Oceans Canada (DFO) as part of the Atlantic Zone Monitoring Program. Ship time and monitoring data could be leveraged to perform a dedicated experiment during the CalVal phase.

The Mediterranean as a Lab for Developing Fine-Scale *in situ* Strategies

Two SWOT crossovers fall within the western and eastern Mediterranean basins, respectively. One on the northern flank of the Algerian current, between Algeria and the Balearic Island; and one in the middle of the Rhodes' gyre. Due to its small deformation radius compared to the gaps between ground tracks at mid-latitudes, the Mediterranean sea is a region where nadir altimetry is known to capture only a small part of the mesoscale dynamics, and therefore, where SWOT is expected to provide a substantial improvement. The presence of low tides, of relatively weak internal wave dynamics (with peaks of activity mainly confined to specific and known regions), together with low cloud coverage, are further reasons for considering the Mediterranean crossovers in interdisciplinary studies.

Both sites display interesting dynamics. The western site is in a region where meanders of the Algerian current pinch off forming mesoscale eddies that propagate cyclonically from the African coast toward the Balearic abyssal plane. This Algerian current transports fresher water of Atlantic origin possibly enriched by nutrient input along the north African coast. In May 2018, the French-Spanish collaborative campaign PROTEVS-PRESWOT tested the implementation of coupling fine-scale physics with fine-scale biological measurements. The objectives of this joint experiment was to (1) evaluate the interest of the western Mediterranean SWOT crossover, (2) gain experience in multi-platform, multi-institution campaign coordination with the constraint imposed by traces of the SWOT satellite, and (3) explore the dynamics present in this region, that has been scarcely sampled in the past with only some recent high-resolution data collected by underwater gliders (Heslop et al., 2017; Aulicino et al., 2018). This work builds on several previous fine-scale experiments in the Western Mediterranean Sea (Nencioli et al., 2011; Pascual et al., 2017; Petrenko et al., 2017; Marrec et al., 2018).

CONCLUDING STATEMENT

The SWOT fast-sampling phase will provide a three-month window in early 2022, with intensive temporal sampling at the cost of spatial coverage. The opportunity to have *in situ* deployments for instrumenting under SWOT swaths during this period, particularly at crossovers, should not be missed: the comparison between *in situ* data and SWOT synoptic maps will provide an unprecedented view of the fine-scale variability in different dynamical regimes in multiple ocean basins. These data will serve as an empirical basis for interpreting future fine-scale observations over the next decade, quantifying the role of fine-scale dynamics in the Earth system.

AUTHOR CONTRIBUTIONS

Fd'O, AP, JW, AD, ZJ, SM, GG, SSw, SSp, FC, BL, and RM wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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frontiers in Marine Science

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SKIM, a Candidate Satellite Mission Exploring Global Ocean Currents and Waves

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The Sea surface KInematics Multiscale monitoring (SKIM) satellite mission is designed to explore ocean surface current and waves. This includes tropical currents, notably the poorly known patterns of divergence and their impact on the ocean heat budget, and monitoring of the emerging Arctic up to 82.5°N. SKIM will also make unprecedented direct measurements of strong currents, from boundary currents to the Antarctic circumpolar current, and their interaction with ocean waves with expected impacts on air-sea fluxes and extreme waves. For the first time, SKIM will directly measure the ocean surface current vector from space. The main instrument on SKIM is a Ka-band conically scanning, multi-beam Doppler radar altimeter/wave scatterometer that includes a state-of-the-art nadir beam comparable to the Poseidon-4 instrument on Sentinel 6. The well proven Doppler pulse-pair technique will give a surface drift velocity representative of the top meter of the ocean, after subtracting a large wave-induced contribution. Horizontal velocity components will be obtained with an accuracy better than 7 cm/s for horizontal wavelengths larger than 80 km and time resolutions larger than 15 days, with a mean revisit time of 4 days for of 99% of the global oceans. This will provide unique and innovative measurements that will further our understanding of the transports in the upper ocean layer, permanently distributing heat, carbon, plankton, and plastics. SKIM will also benefit from co-located measurements of water vapor, rain rate, sea ice concentration, and wind vectors provided by the European operational satellite

MetOp-SG(B), allowing many joint analyses. SKIM is one of the two candidate satellite missions under development for ESA Earth Explorer 9. The other candidate is the Far infrared Radiation Understanding and Monitoring (FORUM). The final selection will be announced by September 2019, for a launch in the coming decade.

Keywords: ocean current, tropics, Arctic, Doppler, altimetry, sea state, remote sensing, ocean waves

1. SCIENCE GAPS AND SKIM OBJECTIVES

Satellite altimetry, combined with gravimetry and *in situ* drifter climatology, has provided a wealth of observations on surface currents during the past 25 years. Away from the Equator, the altimetry constellation resolves spatial scales larger than 200 km wavelength and time scales larger than 2 weeks (e.g., Ducet et al., 2000; Rio et al., 2014; Morrow et al., 2019). Large gaps remain in the observation capabilities of currents, winds and waves, especially in the Tropics, for extreme winds, and for frontal areas or small-scale processes that require high-resolution measurements. These are particularly important at high latitudes. Development in the understanding of radar echoes from the oceans in Ka-band (Yurovsky et al., 2017), allowing higher resolution measurements, and of Doppler measurements in general (Chapron et al., 2005; Yurovsky et al., 2018) show that it is feasible to measure surface currents more directly. Responding to a fast-track call from the European Space Agency, SKIM leverages the development of near-nadir instruments such as SWIM (Hauser et al., 2017) with addition of Doppler processing. This combines a classical nadir altimeter with oblique beams, all operating in Ka-band. This instrument design offers a unique opportunity to explore ocean circulation beyond geostrophy and develop a new generation of global ocean circulation observing system, building on proven altimetry techniques. Other approaches, combining higher incidence angles scatterometry techniques with new antenna technology are also under development (Chelton et al., 2019).

Today's limited knowledge of currents is particularly problematic around the Equator, since it limits our capability to analyze and predict the mixed layer heat budget because the surface temperature variability is driven by ocean dynamics, with far-reaching impacts on the global climate (Hummels et al., 2014). Ocean assimilating models and reanalyses have little skill in reproducing equatorial surface currents, particularly meridional velocity fluctuations that peak at intraseasonal timescales (e.g., Schlundt et al., 2014), resulting in limited seasonal weather forecasting skills. Measuring surface currents with an accuracy of 0.1 m/s on each component (zonal and meridional) for monthly averages at 300 km wavelengths and larger would provide a great step forward in our understanding of equatorial dynamics.

The high latitudes including ice-covered regions, and in particular the Arctic, are other regions with poor measurements of surface currents. These currents are important from a climate perspective as they transport freshwater from river run-off in the Arctic basin and melting of the Greenland ice sheet, to the North Atlantic where it can modify the intensity of deep water formation (e.g., Lique et al., 2016), impacting the global ocean circulation. Retrieving geostrophic currents from altimetry in ice-covered regions is now possible (Armitage et al., 2017, 2018), albeit at too low resolution compared to the dominant energy-containing structures, with horizontal scales characterized by the Rossby deformation radius, typically smaller than 10 km in these regions. Both small-scale eddies and wind-driven currents must be resolved in the ice-covered regions to better quantify and understand the cross-shelf fluxes of heat and freshwater (e.g., Spall et al., 2018; Stewart et al., 2018), the location and evolution of the polar and subpolar gyres (Armitage et al., 2017, 2018; Dotto et al., 2018), as well as the regions of deep water convection (e.g., Lique and Thomas, 2018).

Figures 1D–F illustrates the intense circulation patterns across the ice edge that are expected from numerical modeling but only known qualitatively because quantitative analysis methods using optical or SAR image pairs fail due to its rapid dynamics. The Arctic marginal ice zone is a "mare incognitum" that, by the year 2030, is predicted to expand significantly, under the combined effect of atmospheric and oceanic warming, enhanced ice fragmentation by waves (Aksenov et al., 2017) and increased influence of ocean mesoscale activity (Manucharyan and Thompson, 2017). Measurements are missing to address the questions on freshwater transport and ice edge evolution. SKIM will be the first mission to provide much needed data on surface currents, ice drift and wave spectra (e.g., Stopa et al., 2018), at higher spatio-temporal resolution than is available today. These observations are needed to improve the parameterizations of turbulent fluxes, sea ice rheology, wave-ice interactions, and ocean circulation in climate models and weather forecasting systems.

Resolving waves down to 30 m wavelength, SKIM measurements will provide accurate estimates of the Stokes drift profile in oceans, marginal, and inland seas. Combined with the surface current measurement, Stokes drift data will lead to more accurate analysis and simulation of the poorly known pathways of floating material such as (plastic) debris, abandoned fishing gear, and biological material (Maes et al., 2018; van Sebille et al., 2018). For example, Fraser et al. (2018) showed that kelp found on Antarctic coastlines could only have traveled from lower-latitude sites where it normally grows, thanks to the southward Stokes drift that opposes the northward Ekman transport. As Lagrangian pathways are typically very sensitive to the flow field, accurate knowledge of the surface flow improves our ability to track surface floating debris and determine how microplastic at the surface ocean is transported from coastlines into the open-ocean accumulation zones (Lebreton et al., 2018).

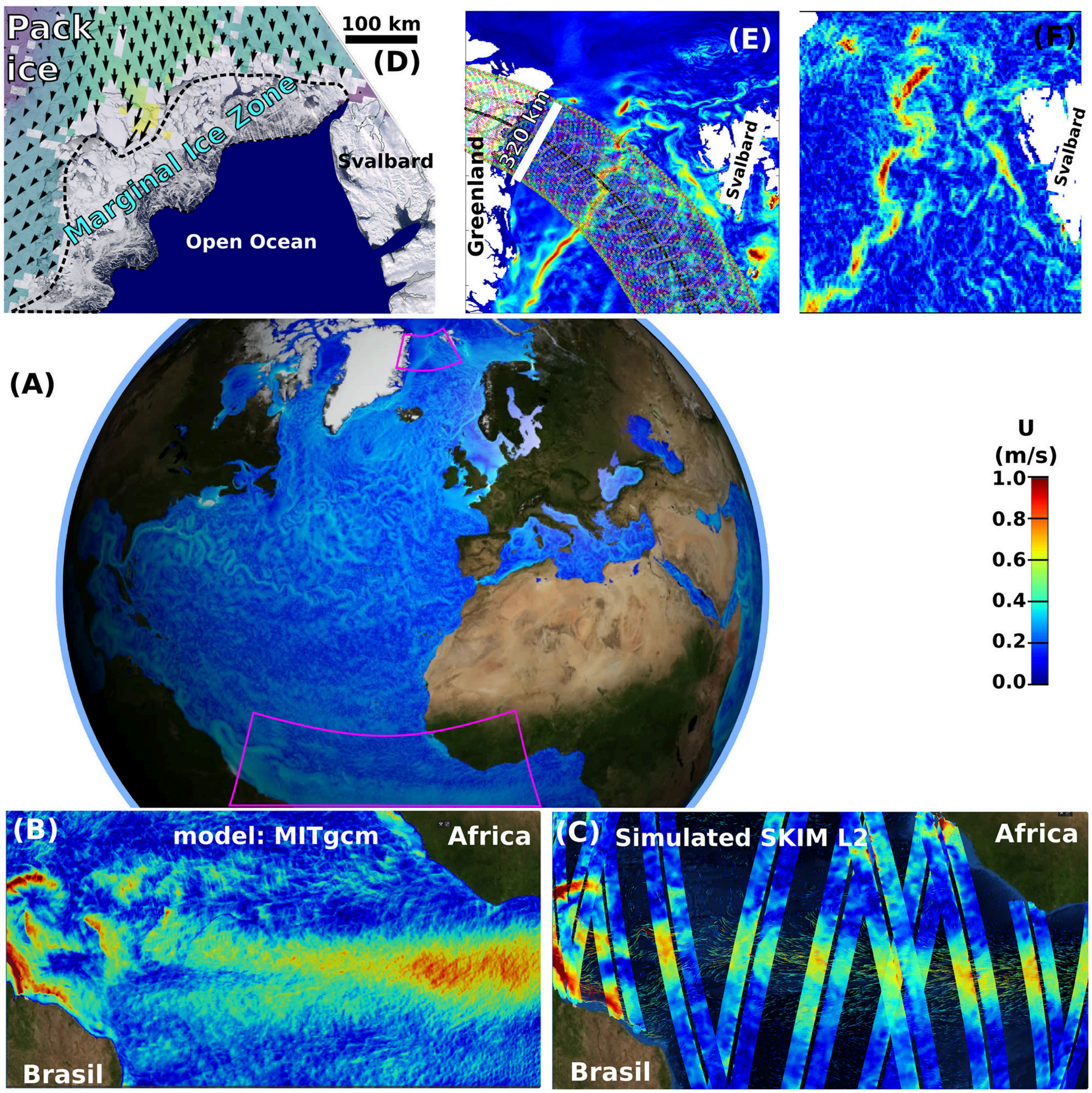

FIGURE 1 | (A) Example snapshot of the global ocean current magnitude (color) as given by the MITgcm 1/48° global model simulation LLC4320 (Rocha et al., 2016), containing density-driven, wind-driven, and tidal currents. The pink boxes around Fram strait and the tropical Atlantic correspond to the other panels. The color bar corresponds to **(B,C,E,F)**. **(B)** close-up on the Tropical Atlantic, and **(C)** a 1-day coverage by SKIM including realistic measurement uncertainties. The central part of the swaths is masked where uncertainties on the along-track velocity component are largest. **(D)** Example of marginal ice zone in Fram strait viewed with optical imagery and characterized by ice bands along the meandering ice edge, with large floes in the ice pack. Ice drift (colors and arrows) is estimated over the ice pack from Sentinel-1 image pair correlations, courtesy of A. Korosov (NERSC). **(E)** Modeled ocean circulation at high resolution (Hutter et al., 2018) showing intense ice-edge jets and Svalbard coastal current that would be observed several times a day by SKIM. The footprints of SKIM across a 320-km swath are represented by small colored circles. **(F)** Multi-swath surface current magnitude including realistic measurement uncertainties. This figure is adapted from The SKIM Team (2017).

The combination of surface currents and wave measurements are also needed to better understand high sea states (Ardhuin et al., 2017; Quilfen et al., 2018) and extreme individual waves (Fedele et al., 2016). As currents define the spatial patterns of sea states at scales under 200 km, they also impact and coastal hazards in a way that is poorly known, contributing to large uncertainties in extreme coastal sea levels (e.g., Guza and Feddersen, 2012; Dodet et al., 2018).

The ocean uptake of greenhouse gases is highly variable in space and time, and has so far been responsible for the absorption of about 25% of the total anthropogenic CO_2 (Le Quéré et al., 2016). This flux is strongly influenced by horizontal transport across high gradient regions. Among these, continental shelves, covering just ∼5% of the world ocean's surface, play an important role in the global carbon. The heterogeneous nature of shelves (e.g., Canals et al., 2006; Bröder et al., 2018), and the difficulty to obtain reliable current estimates there, means that carbon dynamics are often poorly quantified and monitored within these regions. Accurate knowledge of surface water velocities across continental shelf boundaries, vertical shear and turbulence, and surface divergence will improve our ability to monitor how the oceans are impacted and reacting to a changing climate.

We need better measurements of surface currents and waves for all the scientific and societal questions listed above, and many other applications (The SKIM Team, 2017). This is critical to better understand the ocean's role in the Earth system. With SKIM, kinematic variables (surface current, ice drift, waves) can be resolved at smaller scales than those at which dynamic variables (sea level, wind stress) are available today, and complementary to planned higher resolution missions such as SWOT for sea level (Morrow et al., 2019), and CIMR for surface temperature and salinity (Kilic et al., 2018).

2. SKIM MEASUREMENT PRINCIPLE

The SKIM mission concept, now being studied, is designed to fly in tandem with the operational satellite MetOp-SG(B), following a sun-synchronous orbit at an altitude of 824 km. The main innovation is the combination of rotating beams similar to SWIM on CFOSAT, here with incidence angles $\theta_i = 0$ (nadir), 6 and 12°, with a Doppler capability that will measure the surface velocity vector and ocean wave spectra across a 320-km swath.

The sampling properties of SKIM are summarized and illustrated in **Figure 2**.

Starting with the lowest level data in **Figure 2A**, SKIM measures backscattered power and Doppler velocity in range-resolved beams with 0.7-m line of sight resolution. For 12° incidence, this gives a ground-projected resolution of 3.5 m. The velocity is given by the phase different of consecutive pulses (pulse-pairs) transmitted at a frequency of 32 KHz. This high pulse repetition frequency guarantees a high coherence between consecutive pulses. These range-resolved data correspond to averages in the azimuth direction, so that all patterns are averaged out except for features, including modulating waves, perpendicular to the range direction. This is the principle of the "matching wavefront technique" demonstrated with airborne radars (Jackson et al., 1985), and now working in space with the Ku-band SWIM radar on CFOSAT. SWIM uses much larger (18 km) footprints than SKIM, and SKIM includes a Doppler processing that is not available on SWIM. SAR-unfocused processing is used on SKIM to improve azimuthal resolution, down to 300 m, and enhance the modulation signals (see Nouguier et al., 2018). This resolution in range and azimuth will be also used to remove outliers within the radar footprint, such as the ship that appears as a white spot in **Figure 2C**, and to correct for Doppler biases due to variations of backscatter power with azimuth. Each footprint produces measurements of the current velocity along the local range direction, and a wavenumber spectrum of waves propagating to and from the range direction, similar to the SWIM instrument on CFOSAT (Hauser et al., 2017), but resolving shorter wave components, down to 30 m wavelength compared to 70 m with SWIM. These footprints are arranged in the pattern shown in **Figure 2D**.

The combination of all beams across the 320 km wide swath shown in **Figure 2D** is such that each 30 × 30 km square contains at least two measurements, giving the two components of the current vector. The full directional wave spectrum is obtained over a 75 × 75 km box. As discussed by Rodríguez et al. (2018) for the DopplerScat airborne instrument, this viewing geometry suffers from a Geometrical Dilution of Precision, well known for coastal HF radar instruments. Namely, the outer part of the swath mostly contains measurements of the cross-track velocity component while at nadir only the along-track velocity is measured. This, however, can be mitigated using a cross-track estimate of the geostrophic part of the current using the sea surface height anomaly given by the nadir beam.

The most novel measurement of SKIM is the line of sight velocity V_{LOS} using off-nadir beams. Given the incidence θ_i, the ground projection into a radial component $V_{\mathrm{LOS}}/\sin\theta_i$ that contains a non-geophysical contribution $V_{\mathrm{NG}}/\sin\theta_i$ due to the satellite velocity (around 7 km/s), and Earth rotation (around 400 m/s). The residual, a few meters per second, is the geophysical velocity. In the case of the baseline pulse-pair processing, it contains a wave contribution to the Doppler U_{WD} of the order of 1.5 m/s similar to the one measured with Envisat (Figure 5 in Chapron et al., 2005), and the surface current, of the order of 0.3 m/s, averaged over the top meter. An experimental delta-K processing with three fixed delta-K bands will also be implemented. This is similar to HF radar with a well-known U_{WD} equal to the phase speed associated to the selected wavelength and a current averaged over different depth ranges, typically the top 5, 12, and 20 m. Therefore, SKIM will give complementary estimates, from pulse-pair and delta-K processing, of the near-surface current from the V_{LOS} integrated over different depths,

$$U = (V_{\mathrm{LOS}} - V_{\mathrm{NG}})/\sin\theta_i - U_{\mathrm{WD}} = U_{\mathrm{GD}} - U_{\mathrm{WD}}. \quad (1)$$

The accuracy of SKIM current retrieval relies on excellent pointing retrieval and the combination of wind vector, from MetOp-SG(B), and wave parameters from both the nadir and oblique beams, in order to estimate U_{WD} within a few percent.

The contemporaneous measurements of ice and rain detection from the MWI radiometer on MetOp-SG(B) will provide additional flag-setting capabilities that are otherwise based on the variance of backscatter and Doppler within each SKIM footprint. Also, MWI water vapor will be used in the wet tropospheric range correction for the nadir beam. More importantly, the contemporaneous measurement of wind vectors from SCA on MetOp-SG, with currents and waves from SKIM, opens

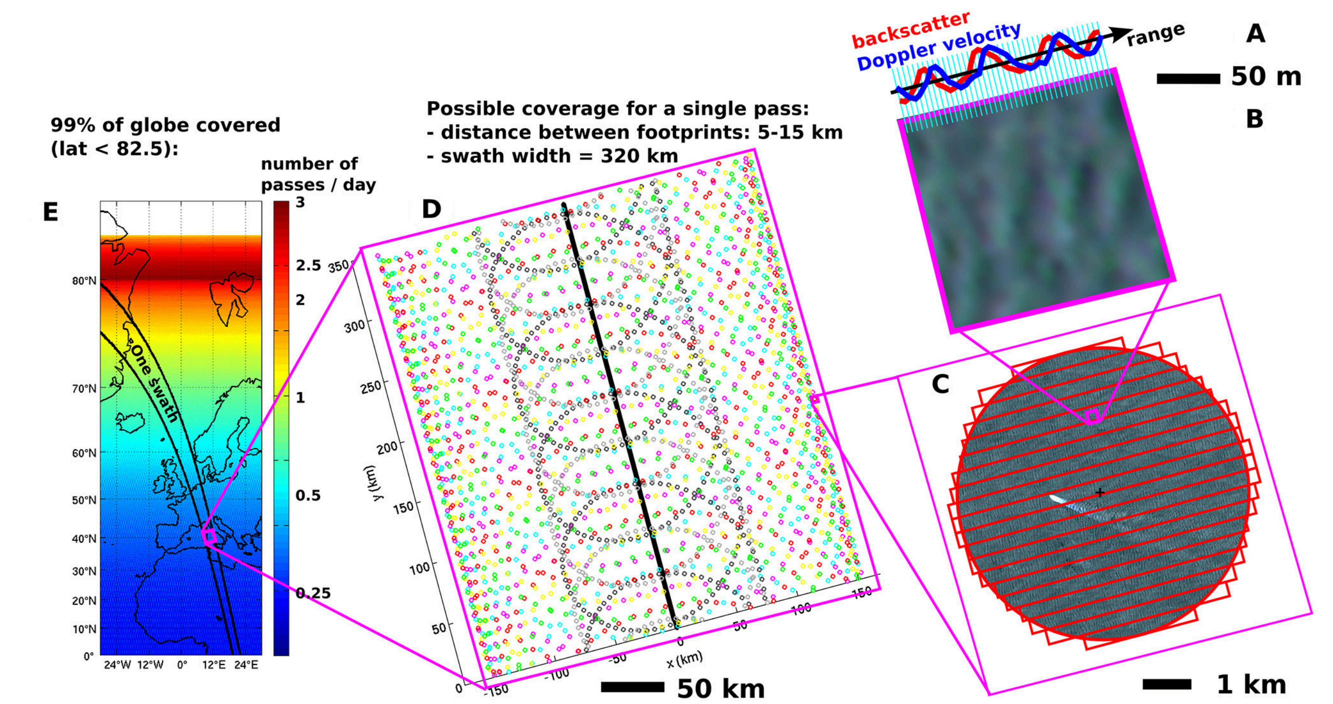

FIGURE 2 | Spatial scales covered in the SKIM measurement, from **(A)** the range-resolved Doppler velocity and back-scatter power that correspond to 2,048 range gates at 0.7 m resolution (cyan lines). The data in **(A)** corresponds to an average over the azimuthal direction, perpendicular to the range direction. The averaged features include the wind-generated waves that appear in **(B)**, as resolved in a Sentinel-2 image. These measurements are made within footprints such as shown in **(C)** that have a diameter of 6 km. Yet, different azimutal "strips" with 300-m resolution can be separated (red boxes in **C**). The footprints are sparsely distributed across a 320-km wide swath shown in **(D)**. These footprints are obtained by the rotation of beams on the SKIM radar, with 3 beams looking at 12° incidence in color, 2 beams at 6° in gray, and one beam at nadir in black. The 824 km altitude orbit considered today gives an average revisit time between 8 h and 4 days shown in **(E)**.

possibilities for a wide range of applications. Just like the full wave spectrum measurement will lead to a revisit in the analysis of wave-induced biases in nadir altimetry, this first measurement of full wave spectra and scatterometer winds will also be unique for estimating and correcting systematic currents (Quilfen et al., 2004) and sea state biases in wind retrievals. The combination of the two missions is also a distinctive opportunity to refine our understanding of air-sea energy (wind work) and momentum (wind stress) fluxes.

SKIM provides a higher spatial resolution than today's altimeter constellation, comparable to the resolution of SWOT, thanks to a wider swath. Because smaller scales move faster, this new data will bring particular challenges related to the aliasing of near-inertial currents, semi-diurnal internal tides, and diurnal cycles of currents that are important in the tropics. This may call for a separation of unbalanced (wind-driven, near-inertial, internal tides) and balanced (i.e., geostrophic) motions that is a very active topic of research, in particular in the context of the SWOT mission (e.g., Torres et al., 2018; Morrow et al., 2019). Although the average time revisit of SKIM (4 days) is large, part of the fast motions are coherent over 4 inertial periods and relatively large horizontal scales (e.g., Kim and Kosro, 2013). Ongoing work suggests that inertial oscillations in the SKIM data may be separated from the more slowly-evolving motions. These efforts are complementary to those focused on the sea surface expression of internal waves in the context of SWOT (Morrow et al., 2019). Finally, with a launch date in the coming decade and a design lifetime of 5 years, SKIM may fly for some time together with SWOT, with highly complementary measurements for the joint analysis of balanced and unbalanced motions, and their interactions.

3. EXPECTED PERFORMANCE

The main requirement for surface velocity measurement for SKIM is related to the scientific applications described above with a root mean square accuracy of 0.07 m/s for each velocity component, zonal and meridional, for wavelengths larger than 100 km, and time scales over 15 days. The spatial scales are relaxed to 200 km for tropical latitudes. The performance of SKIM is thus tested by verifying that simulated SKIM measurements, based on modeled currents and waves, are consistent with the input model fields. The modeled currents used here, from the MITgcm, probably overestimate the internal wave energy by about a factor 2, and underestimate the near-inertial energy by about a factor 2 (Menemenlis, personal communication). These biases are not yet corrected for when the SKIM performance is evaluated, and we expect that the effective SKIM resolution found here may be slightly optimistic away from the tropics due to the underestimated near-inertial energy.

At present, the main source of uncertainty in our retrieval of the surface current is due to the uncertainty on U_{WD}. At Ka-band

and for incidences less than 20°, U_{WD} is of the order of 25 times the radial component of the surface Stokes drift U_S (Nouguier et al., 2018; Yurovsky et al., 2018), and U_S is approximately 1.2% of the radial wind component (Rascle et al., 2006); (Peureux et al., 2018).

Accurate measurements of the geophysical surface velocity U_{GD} require a very accurate knowledge of the platform attitude, and characterization of the backscatter inhomogeneities within the footprint, which can be due to rain, wind variability, slicks, ships, etc. For the rotating SKIM configuration, the pitch and roll of the radar beam can be estimated from the variation in back scatter cross-section across the footprint (Ardhuin et al., 2018). More crucial is the mis-knowledge the yaw pointing. A yaw error of 0.001° causes a Doppler shift of 30 Hz amplitude for $\theta_i = 12°$, and is equivalent to a mean cross-track current error of $\approx$ 10 cm/s. The requirements on the yaw knowledge for the SKIM radar has thus been refined to take advantage of the rotating beam geometry using a data-driven approach similar to Rodríguez et al. (2018), with a residual attitude-related uncertainty on the retrieved current of a few centimeter per second, accomodated within the mission requirements.

The separation of wave U_{WD} and current U contributions to the Doppler velocity is complicated by the natural correlation of waves and currents at the scales of interest (Ardhuin et al., 2017). Previous Doppler current measurements (Rouault et al., 2010; Martin et al., 2016) used a wind-derived proxy to correct for the wave bias. However, for any given location, U_{WD} has root mean square variations of ±40% for any wind speed, due to the variability in the sea state (Ardhuin et al., 2018). Adding sea state parameters from the resolved modulations and the near-nadir measurements of wave height and mean square slope lead to an uncertainty on U_{WD} that is under 10%, accounting for 30–50% of the overall uncertainty on the surface current retrieval, depending on the strength of surface current gradients and on the local wave field (Ardhuin et al., 2018). We have thus investigated different regions of interest to estimate SKIM uncertainties. Looking at the along-track coherence of the cross-track current between the simulated SKIM currents and the input surface current fields, we define the effective resolution as the wavelength at which the coherence drops below 0.5.

Starting from single footprints, 6 km in diameter, the root mean square uncertainties for the radial current component are around 0.1 cm/s. For gridded current components, uncertainties are reduced by spatial averaging. Our current approach uses optimal interpolation leading to an effective resolution that is within the requirements, typically around 70 km wavelength when considering a single swath corresponding to a snapshot of the surface current. When considering the time evolution of the surface current and comparing that to a multi-swath SKIM simulated product, the smaller scales are not resolved because they move faster, and the effective resolution ranges from 70 km at high latitude, to 250 km at the equator, as illustrated in **Figure 1**. We typically find 80 km at mid latitude which is half of the effective resolution of today's nadir satellite altimeter constellation.

Future work will certainly better take wave-current correlations into account. A direct assimlation of the total geophysical velocity in a coupled wave-current models should be an optimal use of the data, fully taking advantage of the combined wave and current measurements.

4. CONCLUSIONS

SKIM builds on the proven altimetry technique for sea surface height and derived geostrophic near-surface current estimates, adding a global monitoring of all ageostrophic flow components. SKIM will for the first time measure the full surface current vector at the same time as highly resolved two-dimensional and unambiguous wave spectra over the global ocean. This will reveal the transport of heat in the tropics, freshwater in the Arctic and plankton or plastics everywhere with unprecedented resolution. SKIM will also resolve the sea states in all marginal and enclosed seas. By flying in formation with MetOp-SG(B), SKIM will allow unique analyses of air-sea fluxes that will use wind vector measurements, rain rate, and sea ice concentration.

All this will happen if the SKIM concept is indeed selected to become the 9th ESA Earth Explorer mission, a selection that will happen in Summer 2019 based on the result of simulations and campaign analysis, that will benefit from the mobilization of the oceanographic community and demonstrate the soundness of the SKIM concept. We hope to celebrate this success at the upcoming OceanObs'19 conference, and we will work with the community to define a roadmap on the development of tools and validation plans. These are needed to facilitate the uptake, over the next decade, of the new globally measured variable that is the total surface current vector.

AUTHOR CONTRIBUTIONS

DM and FA provided the numerical model output that was analyzed for SKIM performance by LG and CU. J-MD, FC, and CU performed the analysis of attitude effects and data-driven attitude corrections. PB, FA, SC, CD, DM, JS, MT, and EvS wrote the science objectives. All authors contributed to the final editing of the manuscript.

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Innovative Real-Time Observing Capabilities for Remote Coastal Regions

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Remote regions across Alaska are challenging environments for obtaining real-time, operational observations due to lack of power, easy road access, and robust communications. The Alaska Ocean Observing System partners with government agencies, universities, tribes and industry to evaluate innovative observing technologies, infrastructure and applications that address these challenges. These approaches support acquisition of ocean observing data necessary for forecasting and reporting conditions for safe navigation and response to emergencies and coastal hazards. Three applications are now delivering real-time surface current, sea ice, and water level data in areas not possible a mere 10 years ago. One particular challenge in Alaska is providing robust alternative power solutions for shore-based observing. Remote power options have been evolving alongside resilient technologies and are being designed for freeze-up conditions, making it possible to keep remotely deployed operational systems running and easy to maintain year-round. In this paper, three remote observing approaches are reviewed, including use of off-grid power to operate high-frequency (HF) radars for measuring surface currents, a real-time ice detection buoy that remains deployed throughout the freeze-up cycle, and a high-quality water level observing alternative to NOAA's National Water Level Observing Network (NWLON) installations. These efforts are highly collaborative and require working partnerships and combined funding from other interested groups to make them a reality. Though they respond to Alaska's needs including Arctic observing, these approaches also have broader applications to other remote coastal regions.

Keywords: currents, ice detection, water level, GNSS reflectometry, modeling, forecasting

INTRODUCTION

Alaska has been experiencing dramatic changes in the past decade, especially in the Arctic. March 2015 and 2016 Arctic sea ice extents set new record lows in the winter sea ice extent maximum for the entire satellite record starting in 1979 (Viñas, 2016; NASA, 2016). December 2017 continued this trend and experienced the second lowest ice extent in the satellite record (NSIDC, 2018; Walsh, 2018). Later freeze-up dates in the fall and earlier break-up dates in the spring are occurring for both the Bering Strait and Chukchi Sea regions (Mahoney et al., 2014; Johnson and Eicken, 2016; DeMarban, 2018a,b; Samenow, 2018). Sea ice coverage has decreased to the point that existing northern shipping lanes around the world are open for longer periods of time (Masters, 2013) and are projected to experience a continued increase in marine vessel traffic (Arctic Council, 2009). This heightens the likelihood of ship groundings and the potential for oil spills in the region (Roelevan et al., 1995; Merrick et al., 2002). Already, the United States and nations including Russia, China, Korea, and Japan are eyeing increased access and use of this new Arctic Marine Highway for shipping, offshore oil, gas and mining activities, and fishing (Arctic Council, 2009; Zysk, 2014; Pan and Huntington, 2016; Tonami, 2016; Quillérou et al., 2017). To this end, the United States Arctic, comprised of the Beaufort, Chukchi and Bering Seas, needs a robust marine and coastal observing infrastructure providing real-time maritime observations to support national interests in this region, including navigation safety, hazard risk planning, and incident response (U.S. Navy Dept, 2009; U.S. Coast Guard, 2013). However, to date, the United States Arctic has been significantly under-observed, especially compared to other United States coasts.

Alaska is a challenging environment for obtaining real-time observations due to the lack of coastal infrastructure including grid-tied-power, easy road access and robust communication systems. During the past decade, the Alaska Ocean Observing System (AOOS) has partnered with government agencies, universities, tribes, and private industry to evaluate and demonstrate creative solutions to filling information gaps by establishing observing networks and using technologies and infrastructure that circumvent some of these challenges. In this review, we highlight three of these solutions and provide the motivation, application and a brief evaluation on successes that demonstrate the viability of these technologies for Alaska and other remote maritime observing needs.

METHODS AND APPROACH

The Alaska Ocean Observing System and Regional Collaborations

The sheer size of the Alaska region requires extensive collaboration and leveraging of other programs to accomplish the AOOS mission, which is to increase observing and forecasting capacity in all regions of the state, especially in the Arctic and the Gulf of Alaska. AOOS supports key observational assets while identifying and working to fill information gaps.

The Alaska Ocean Observing System is guided by a governing board made up of state and federal agencies, the University of Alaska and other Alaska research institutions, and representatives of the private sector including marine navigation, fisheries, oil and gas industries, and tribes. Strong stakeholder relationships and active engagement and outreach programs ensure the most urgent observing needs are prioritized as described in the AOOS Strategic Operations Plan (Alaska Ocean Observing System [AOOS], 2016). To enlist stakeholder input used to prioritize observing initiatives, AOOS hosts multiple observing network consortiums. The Alaska Water Level Watch (AWLW) is a collaborative group working to improve the quality, coverage, and accessibility to water level observations in Alaska's coastal zone[1,2]. The Alaska Ocean Acidification Network[3] and the Alaska Harmful Algae Bloom Network[4] are two other examples of AOOS lead, topical working groups. These networks provide forums for stakeholder participation, collaboration and input to observing priorities, and they support and host workshops, pursue funding opportunities and proposals, as well as conduct outreach activities.

Alaska Ocean Observing System also actively supports and provides public access to regional real-time and historical data through the largest collection of regional and Arctic data, models, and visualization tools, powered by a state-of-the-art high-performance computing center. Through data portal tracking, user feedback and data requests, AOOS identifies where users need more information. All of these efforts provide valuable feedback on the need for specific data and information across the region, and through AOOS, informs the national IOOS program on critical observational data gaps and infrastructural and technology needs required to fill these gaps.

Operating High Frequency (HF) Radars in Remote Regions Off the Grid

High frequency (HF) radar systems are shore-based installations that measure high-resolution speed and direction of surface currents across large areas of the coastal ocean at hourly intervals in real-time. The present state of the United States national HF radar network for measuring surface current has resulted from nearly 40 years of research, development and application (Stewart and Joy, 1974; Teague et al., 1975; Holbrook and Frisch, 1981; Janopaul et al., 1982; Fernandez et al., 1995; Chapman and Graber, 1997; Graber et al., 1997; Essen et al., 2000; Paduan et al., 2001). HF radars are highly suitable for remote monitoring as they can operate autonomously under any weather condition. The spatial-map time series of HF radar surface currents provide enough detail for important applications including ecosystem research and management, numerical modeling and prediction, search and rescue, hazardous materials spill response, and overall increased marine domain awareness. HF radar signals have also been evaluated as a tool for vessel detection in areas lacking Automated Information System (AIS) capability (Roarty et al., 2013a,b), increasing their potential utility for remote observing.

Challenges With HF Radar Implementation in Alaska

Changes occurring in the Arctic, the expected increase in vessel traffic and need for predictive capabilities in ocean and ice forecasting are just a few of the motivations to increase HF radar observing in Alaska, especially along the Bering Sea and Bering Strait and the north slope in the Beaufort Sea. Though

[1] https://aoos.org/alaska-water-level-watch/
[2] https://www.facebook.com/AlaskaWaterLevelWatch/
[3] https://aoos.org/alaska-ocean-acidification-network/
[4] https://aoos.org/alaska-hab-network/

there is an extensive HF radar network operating continuously along much of the contiguous United States coastline[5], Alaska currently has only three HF radar stations, which operate along the northwest coast on the Chukchi and western Beaufort Seas. Alaska lacks adequate HF radar installations, due in part to the limited available power and transportation infrastructure across much of the Alaska coastline.

A 5 MHz HF "long-range radar" are most common as they provide the best coverage and can transmit over radar distances up to 200 km using on the order of 7.5 kWh/day. Most HFR systems in the United States obtain power from the onshore power grid, and it is this dependency that has severely limited HF radar application in Alaska. Where power is available, namely in remote coastal communities that struggle with generating their own power needs, site location may not yield the optimal radar mask for sampling ocean currents. Remote installations of HF radar in Arctic and sub-Arctic Alaska must also consider difficult and costly logistics, demanding environmental conditions such as high winds, sub-freezing temperatures, salt-laden maritime air and icing, inquisitive, and potentially disruptive, wildlife (rodents, foxes, and bears), and site permit requirements.

HF Radar Power Solution – The Remote Power Module (RPM)

To solve the power problem with HF radar installations in Alaska, engineers and scientists from the University of Alaska, Fairbanks (UAF) College of Fisheries and Ocean Sciences developed an HF radar remote power module (RPM) (Statscewich et al., 2011, 2014). The RPM (**Figure 1**) is a stand-alone device for long-term deployments that minimizes permit issues associated with diesel generators and logistical costs associated with refueling and maintenance. The RPM design facilitates setup and transport to remote sites using small vehicles, and contains subsystems for power generation, satellite communications, and power performance monitoring. A battery bank with a 5-day power reserve is charged primarily by wind and solar, and secondarily by a biodiesel generator. The current system used in Alaska is specifically designed for high latitudes, but can be modified for remote coasts elsewhere. Two of the three Alaska HF radar stations are currently powered by RPMs. The UAF team has also successfully operated three HF radars in Antarctica, two of which were powered exclusively by RPMs. In 2019, AOOS and UAF will install two additional HF radars in the Bering Strait region with one system utilizing an RPM.

[5]http://hfradar.ndbc.noaa.gov

FIGURE 1 | Picture of an Arctic HF radar installation to the left and its corresponding remote power module (RPM) shown to the right. (Photo credit: Hank Statscewich, UAF, AK).

Lessons Learned

The RPM design has proven reliable for the "High Arctic" and the Antarctic summer, but has several critical flaws, namely in the ability to keep electronics warm in deep winter. Engineers have since developed an insulated, thermo-regulated enclosure for the sensitive HFR electronics. Fortunately, heavy snow has not been an issue, as the foundation keeps the instrument enclosure and the bottom of the solar array nearly 1.5 m above the ground. Solar panels are kept at a fairly steep angle of 65 degrees, so snow tends to slide off, keeping them exposed to sunlight. To ensure real-time data delivery, an add-on iridium satellite-based data telemetry system will be implemented to provide a reliable data back-haul as a fail-over should the Hughes Net telemetry system go down. The three RPMs currently in the Arctic have produced nearly 90% of their total power from the wind, and similar performance at the new Bering Strait location is expected, but with periodic bursts of much higher winds than are typically seen on the north slope. To accommodate the higher winds, the wind turbine masts have been reinforced with a grade 80 stainless steel insert and deployed wind turbines will have a smaller rotor diameter to avoid excessive blade deflection and mast strikes. The power delivery sub-panel for the RPM has also undergone a major revision and will be much more compact, modular and integrated. The net result of these modifications will reduce total cost to build and purchase the RPM, enable quicker installation in harsh environments and provide additional system health monitoring, expediting a more thorough remote troubleshooting capability.

Real-Time Ice Detection Buoys for Maritime Domain Awareness and Ice Forecasting

In the United States Arctic, federal agencies, shipping and the oil and gas industries require an accurate method of predicting sea ice formation for offshore operations and maritime safety. One aim is to avoid costly, premature or delayed cessation of marine operations caused by inaccuracies in model predictions or satellite detection of sea ice formation. Despite the exceptional ability to forecast the onset of sea-ice formation, sea ice models remain challenged by the lack of information about how the vertical density gradient (induced by both temperature and salinity) over the shelf evolves as a function of air-sea heat fluxes. This information is limited as real-time water column observations are typically restricted to seasonal mooring operations that can only be conducted with vessel support during ice-free conditions. However, it is precisely during the breakup and freeze-up transitions when these observations are most needed for accurate ice modeling and forecasting efforts.

A Real-Time Ice Detection Buoy System (IDB)

The IOOS Ocean Technology Transition (OTT) program, sponsoring the transfer of emerging marine observing technologies into operational-ready platforms, supported the University of Alaska (UAF), industry partner Pacific Gyre and AOOS to fully develop and deploy an ice detection buoy (IDB) system that inexpensively and accurately reports the seasonal evolution of the thermohaline structure in the water column through the freeze-up cycle. Data from the IDB are needed by models to determine when the onset of offshore sea ice formation begins, while providing guidance for improving remote sensing algorithms for frazil ice detection, a notoriously difficult process for remote sensing ice satellites. The IDB itself is designed to transmit data real-time via iridium satellite through the onset of ice formation, at which time an expendable surface buoy is remotely detached by an operator to prevent loss of the subsurface mooring just before ice moves in or freeze-up commences. The subsurface mooring and sensor array remain in the water below ice keel-depth, recording data through the following breakup cycle and planned recovery.

Alaska IDB Sea Trials

The first IDB was deployed in 2015 on the Chukchi Shelf in 40 m water depth. The mooring was equipped with a sea surface thermistor, five subsurface SBE 37 IMM Microcat Conductivity and Temperature sensors (8,10, 20, 30, and 40 m), subsurface floatation below the expected ice keel-depth, an acoustic release and an expendable surface float equipped with iridium antennae for data transmission[6]. The IDB successfully reported the vertical temperature and salinity structure of the Chukchi Sea shelf in real-time prior to and during the 2015 freeze-up cycle. Operators released the expendable surface buoy when the vertical density gradient eroded in early November and satellite imagery indicated the main ice pack was less than a day from over-riding the mooring (Hauri et al., 2018).

The success of this trial buoy lead to the deployment of an identical system in 2017, with support from the NOAA National Weather Service (NWS). 2017 data were displayed real-time on the AOOS data portal as well as shared through the GTS (Global Telecommunications System), which enabled real-time access to the IDB data for use in the NWS Alaska Sea Ice Program (ASIP) forecasting activities. Data were used in the daily ice analysis, 5-day sea ice forecasts, and the 3-month sea ice outlook products. The NWS analyzed the IDB data alongside current satellite imagery in the vicinity of the buoy for a better informed and more complete view of the coupled atmosphere/ice/ocean system. The 2017 IDB was successfully recovered in the late summer of 2018 and the overwintering data are currently being analyzed.

[6]https://aoos.org/ice-detection-buoy/

Lessons Learned

The 2015 subsurface mooring was never recovered, either because the acoustic release failed, or more likely because ice keels moved the mooring by hooking the subsurface floatation. In 2018, a third IDB deployment only reported data for 1 day before going off-transmission due to ice. A passing research vessel recovered the intact mooring, which had moved south from its original deployment position and sustained damage to the antenna. The IDB surface and subsurface floatation clearly puts it at risk of mobile ice any time of year, and the IDB sea-trials have informed several needed modifications for future IDBs, including safeguarding against ice rafts and reinforcing the surface float communications antenna. Despite these risks, the value of capturing the real-time water column density stratification conditions during freeze-up was demonstrated and the success has captured the attention of the NWS and other stakeholders interested in ice freeze-up prediction and forecasting.

A Tiered Data Quality Approach for Observing Water Levels

Accurate water level observations are fundamental for safe navigation, mapping and charting, storm-surge forecasting, informed emergency response, and ecosystem management. Alaska's extensive and remote shorelines are especially under-instrumented with respect to basic water level observations, due in part to regional obstacles including the formation of seasonal ice, the lack of coastal infrastructure needed to install observing platforms and rapid coastal erosion that render conventional water level sensing technologies impractical. Approved NOAA Center for Operational Oceanographic Products (CO-OPS) National Water Level Observation Network (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 as they provide the best solution for all water level data applications, a tiered water level data policy allows for observations with lesser accuracies (Edwing, 2015). The policy stipulates water level data quality tiers A (e.g., NWLON), B and C, matching data accuracy to specific applications (**Table 1**).

The Alaska Water Level Watch (AWLW) partnership is working to augment the existing Alaska NWLON with tiered coastal water level observation products (e.g., real time stations, short-term time series, and high-water mark measurements). The ultimate goal is to make these additional data products public through a robust data management system that parallels the NOAA CO-OPS Tides and Currents online system[7], as this system only hosts Tier A data. AOOS is supporting the initial development of the tiered data portal, and IOOS and NOAA CO-OPs plan to advance development

[7]https://tidesandcurrents.noaa.gov/

TABLE 1 | Minimum criteria for tiered data within NOAA CO-OPS water level program.

Tier	A	B	C
Minimum accuracy (on datum for tier A and B)	10 cm	30 cm	30 cm or accuracy not determined, or minimum benchmarks not installed
Benchmarks	5	3	Not required
Leveling order	Annual 2nd order class 1 better	Biannual 3rd order or GPS derived ellipsoid based	Not applicable
Applications	• Real-time navigation for coasts and Great Lakes • Marine Boundaries • Sea Level Anomalies • Vdatum • Hydrodynamic model forcing and skill assessment • CO-OPS MAPTITE applications	• Hydrographic surveys • Shoreline mapping • General marsh restoration applications • Storm surge • Exceedance • Inundation dashboard	• Academic research • Background oceanographic information • Tsunami
Harmonic constants and predictions	Official NOS product – unrestricted use	Official – use only for Tier B and C applications. Predictions not used in tide tables or NOAA tides	Unofficial – use only for tier C applications. Predictions not used in tide tables or NOAA tides
Benchmark Sheets	Official NOS product – unrestricted use	Official – use only for Tier B and C applications	Not published
Datums	Official NOS product – unrestricted use	Official – use only for Tier B and C applications	Not published
Sea level trends	Official NOS product – unrestricted use	Cannot be used	Cannot be used
Dissemination	Real time or non-real time (determined by AGREEMENT)	Real time or non-real time (determined by agreement)	Non-real time (minimum latency – 24 h), except for tsunami data

(Adapted from Edwing, 2015).

of this capability and make it nationwide through the IOOS Regional Associations.

Remote, Real-Time Water Level Observing Using GNSS Reflectometry

Alaska Ocean Observing System is testing alternative methods that provide Tier B water level information, the minimum accuracy sufficient for computing datums, resolving tidal and subtidal water levels within 10 s of cm, also adequate for understanding flooding events and validating storm surge models and forecasts. Global Navigation Satellite Systems (GNSS) receivers have been demonstrated to provide a quality alternative method for directly measuring water level without a tide gauge, referred to as GNSS-Reflectometry (GNSS-R) (Martin-Neira, 1993; Löfgren et al., 2011; Larson et al., 2012, 2013, 2017; Dawidowicz, 2014; Strandberg et al., 2016; Williams and Nienvinski, 2016). GNSS-R receivers measure water level changes at an oblique angle, and can be installed on existing infrastructure, such as a pier or a building, or directly on land where a clear view of the water surface exists with no obstructions. The basic approach uses reflected GPS satellite signals to determine the height of a reflecting surface, such as the ocean, relative to a stable GPS antenna of fixed local height. The total received GPS signal measured by the antenna is the sum of the direct signal and the reflected signal. The interference between these two signals depends on the satellite altitude in the sky and on the receiver height above the ground. Given the satellite altitude is known, the observed interference pattern as the satellite rises/sets is used to extract the receiver height, after which the antenna height is subtracted to determine the true water level. GNSS-R can be installed and maintained more easily and at significantly lower cost than a traditional NWLON tide gauge while providing high quality Tier B water level information (e.g., Larson et al., 2013). GNSS-R systems do not require much power, and can operate off remotely rechargeable power supplies, such as small solar panels with rechargeable batteries, making them suitable for remote coastal installations. GNSS-R receivers also do not need to be removed prior to freeze-up, hence are especially well-suited for year-round Arctic installations. Real-time (or near real-time) data can be transmitted either by cell phone (if in a community with service), or via an iridium satellite link.

Alaska GNSS-R Pilot Study

Since 2017, AOOS and partners have been exploring GNSS-R water level measuring techniques to determine the efficacy of these systems for use in remote Alaska, and to determine some of the limitations in various environmental settings, such as mountainous fjords commonly found along the Southeast Alaska coast, and low-rise topography coastal areas with large tidal excursions common along the western Alaska coastline and north slope. The NWS is supporting AOOS in testing GNSS-R systems from both a non-profit geoscience consortium UNAVCO[8], and a private industry partner ASTRA, LLC.

Alaska Ocean Observing System and UNAVCO have just started their collaboration, but AOOS and ASTRA, LLC completed their first GNSS-R sea trial in 2018 using ASTRA's commercialized dual frequency GPS system that was initially

[8]https://www.unavco.org/about/about.html

developed for space weather monitoring. These space weather systems have operated in Alaska, including the Arctic, for over 10 years. A year-long pilot study conducted in Seward, Alaska enabled the performance of the ASTRA GPS receiver to be evaluated against water level measurements from a NOAA-operated NWLON station 2 km away. The water level data comparisons between the two methods showed acceptable agreement with the GNSS-R major tidal constituents (M2, S2, N2, K1, and O1) measuring within 5 cm of the NWLON estimates, easily meeting the Tier B water level criteria objective (Janzen et al., 2018).

Lessons Learned

The Seward sea trials using GNSS-R for water level observing have provided valuable logistical installation information for future remote deployments. Seward GNSS-R data indicated that deployment near mountainous regions can block satellite coverage and reduce the data rate during certain times of the day. GPS receivers provide high frequency data rates for water level observing, and fortunately, the reduced data rate did not prevent tidal harmonic and subtidal analyses of the data. However, a period of time when a ship was moored near the GPS receiver caused interference in the data quality, and illustrated the importance of locating installations away from areas frequented by boats.

DISCUSSION

All observing activities in Alaska depend on substantial partnerships and leveraging of resources, as well as enhanced coordination with Alaska coastal communities and tribes. AOOS, as the Integrated Ocean Observing System (IOOS) Regional Association (RA) responsible for coordinating statewide monitoring for Alaska's nearly 44,000 miles of coastline and offshore environments, is not the only entity working in this realm. However, it is the only entity representing state and federal agencies, research institutions and the private sector whose primary mission is to enhance ocean observations to meet a broad range of end user needs. Many of these activities depend on the collaboration among all 17 federal agencies within the NOAA managed national IOOS Program, as well as links to the Global Ocean Observing System (GOOS) and the Group on Earth Observations (GEO). These collaborations should be fostered and enhanced with training and technical support, as well as additional mechanisms for transferring and sharing of funds among federal agencies and with the private sector. As the Arctic continues to become more accessible and receive greater attention and use, a modest investment in additional observing assets in the region – linked to pan-Arctic assets and those in other Arctic regions, will enhance the United States marine domain awareness in the Arctic as well as national and international security.

AUTHOR CONTRIBUTIONS

CJ: AOOS program manager of all projects in mini-review, lead author of this manuscript, lead author of Sections "Introduction," "Real-Time Ice Detection Buoys for Maritime Domain Awareness and Ice Forecasting," and "A Tiered Data Quality Approach for Observing Water Levels," co-author and technical editor of all other sections, analyst for tidal harmonics of GPS reflectometry data discussed in Section "A Tiered Data Quality Approach for Observing Water Levels." MM: AOOS director, lead author of Abstract and Sections "The Alaska Ocean Observing System and Regional Collaborations" and "Discussion," and co-editor of all other sections. TW: lead project investigator on the HF Radar program in Alaska, lead project investigator for the Remote Power Modules used to support HF Radar in Alaska, co-author in Section "Operating High Frequency (HF) Radars in Remote Regions Off the Grid." HS: lead engineer on HF Radar program in Alaska, lead engineer for Remote Power Modules used to support HF Radar in Alaska, lead author of Section "Operating High Frequency (HF) Radars in Remote Regions Off the Grid," and supplied **Figure 1**. PW: lead project investigator for the Ice Detection Buoy project, co-author in Section "Real-Time Ice Detection Buoys for Maritime Domain Awareness and Ice Forecasting." SD: project investigator on the Ice Detection Buoy project and current lead project investigator on the HF Radar program in Alaska, co-author in Section "Real-Time Ice Detection Buoys for Maritime Domain Awareness and Ice Forecasting." RH: NOAA-National Weather Service liaison for the Ice Detection Buoy project, and co-author in Section "Real-Time Ice Detection Buoys for Maritime Domain Awareness and Ice Forecasting".

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Citizen-Science for the Future: Advisory Case Studies From Around the Globe

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The democratization of ocean observation has the potential to add millions of observations every day. Though not a solution for all ocean monitoring needs, citizen scientists offer compelling examples showcasing their ability to augment and enhance traditional research and monitoring. Information they are providing is increasing the spatial and temporal frequency and duration of sampling, reducing time and labor costs for academic and government monitoring programs, providing hands-on STEM learning related to real-world issues and increasing public awareness and support for the scientific process. Examples provided here demonstrate the wide range of people who are already dramatically reducing gaps in our global observing network while at the same time providing unique opportunities to meaningfully engage in ocean observing and the research and conservation it supports. While there are still challenges to overcome before widespread inclusion in projects requiring scientific rigor, the growing organization of international citizen science associations is helping to reduce barriers. The case studies described support the idea that citizen scientists should be part of an effective global strategy for a sustained, multidisciplinary and integrated observing system.

Keywords: citizen science, ocean observing systems, crowd sourcing, bathymetry, king tide, GCOOS, volunteer-collected data, global ocean observing system

INTRODUCTION

Logistical considerations and the high costs of deploying traditional *in situ* ocean observing systems limit their density and thus ability to accurately monitor fine-scale environmental conditions. In the coming years, the combination of youth who are increasingly globally connected and a growing population of retired professionals, poses an opportunity to create a "K to gray" network of citizen scientists with capacity that spans multiple cross-cutting and societal themes. Though not a solution for all ocean monitoring needs, citizen scientists can augment and enhance traditional research and monitoring, increase spatial and temporal frequency and duration of sampling, reduce time and labor costs, provide hands-on Science, Technology, Engineering and Mathematics (STEM) learning related to real-world issues and increase public awareness and support for the scientific process. While there are challenges to overcome before wide-scale inclusion in the ocean observing system enterprise, progress in this as yet underutilized resource is encouraging. The following are examples from around the world of how communities are being meaningfully engaged in ocean observing and the research and conservation these efforts support. **Table 1** summarizes the five examples provided. Each has an introduction to the project, a description of the approaches used and a summary of the results. The paper concludes with identification of challenges and potential solutions for citizen science efforts in the future.

EXAMPLE 1: CITIZEN SCIENCE FOR CLIMATE CHANGE AND BIODIVERSITY OBSERVATIONS

Project Introduction

Svalbard is a Norwegian archipelago that is one of the world's northernmost inhabited areas. Located between mainland Norway and the North Pole, it is a popular destination for tourists and expeditions visiting the area. For years, the Norwegian Polar Research Institute has taken advantage of the opportunity to engage these visitors in monitoring local wildlife. What started as distributing questionnaires to tourists has grown into a community of citizen scientists who contribute information to supplement census data of birds and mammals. The information provided is especially valuable because the volunteers visit places where research projects are seldom conducted. Contributions to monitoring species like polar bears have a high degree of utility because of the accuracy in identification. Including census data from untrained volunteers is more problematic for species of whales and dolphins.

One example of research that volunteers participated in was evaluating the importance of tidewater glaciers to foraging seabirds. Dating back to 1936, there are a number of records in the literature reporting an abundance of seabirds such as foraging kittiwakes, black guillemots, terns and fulmars associated with glaciers. Among the explanations of these records is the idea of "hot spots" whereby some ecological phenomenon accounts for the high concentration of seabirds (Urbanski et al., 2017). Volunteers were recruited to help determine if the reported observations are typical of all glaciers.

Six yacht captains who routinely bring tourists to Svalbard and Greenland were tasked with taking photos along the glacier cliffs. To standardize data processing by the scientists, a pre-determined distance of 200 m from the Svalbard glaciers was established (further in Greenland because of the size and activity of the glaciers). Over the course of three summer seasons, more than 600 georeferenced photos of 35 different glaciers were collected. Scientists analyzed the images, noting the presence of birds and characterizing each glacial bay using information in the literature. In addition to type of glacier, features analyzed included depth, salinity, sill presence, fetch, proximity to open shelf waters, and suspended matter. Statistical analysis was performed comparing the abundance of birds to glacier features. Results indicated that the bird aggregations are randomly distributed across the different types of glaciers and that there were actually no consistent hot spots.

Another example of citizens engaging in the scientific process involves assessing the impacts of climate change on zoogeography. Two species of amphipods, *Gammarus setosus* and *Gammarus oceanicus*, occur on Svalbard. The former is a local Arctic species and the latter is a boreal species. Both are found in the littoral zone, are about two to three centimeters in size, and are relatively easy to spot. They dwell in sheltered sites, almost exclusively under flat, loose stones, making specimens readily available to volunteers at low tide. Scientists had previously conducted research demonstrating that the two species compete for space (Weslawski, 1990). However, in that study only a single fjord was investigated. A large scale survey was desired to determine if increasing temperature was resulting in the northward dispersal of the boreal species, *G. oceanicus*, hence creating more competition with the Arctic species. Tourists visiting remote areas of the Svalbard archipelago were asked to participate in the study, given instructions on how to collect samples, and given small vials with alcohol to preserve samples.

TABLE 1 | Case study examples of citizen science projects.

Advisory case study	Community science goal
Example 1: Citizen Science for Climate Change and Biodiversity Observations	Biodiversity Monitoring
Example 2: Ocean Microbiome and Microplastics Tracking by Citizen Oceanographers	Quantifying Microplastics
Example 3: Encouraging Innovative Supplementary Data Gathering: An International Hydrographic Organization Crowdsourced Bathymetry Initiative	Bathymetric Mapping and Elevation Verification
Example 4: 50,000+ Citizen-Science Collected GPS Flood Extents Used to Validate a Street-Level Hydrodynamic Model Forecast of the 2017 King Tide in Hampton Roads, VA	Real Time Flood Monitoring and Street-Level Inundation Model Validation
Example 5: Citizen Scientists: An Underutilized Resource for the United States IOOS	Enrichment of Observation Systems' Data Viewers through Citizen Science

Three seasons of collection provided sufficient data for scientists to analyze. Results indicate that the range of *G. oceanicus* is being extended poleward (Weslawski et al., 2018).

Volunteers in these citizen science initiatives enthusiastically collected data and were recognized for their participation with acknowledgments in research publications and on project web pages. They provide an excellent example of the ability of volunteers to fill important spatial gaps in research and monitoring projects.

EXAMPLE 2: OCEAN MICROBIOME AND MICROPLASTICS TRACKING BY CITIZEN OCEANOGRAPHERS

Project Introduction

The world's oceans contain an estimated 1.2×10^{29} microbes (Whitman et al., 1998; Bar-On et al., 2018). These organisms are the key drivers of ocean health and form the foundation of the food web. Because of their sensitivity to climate change, the marine microbiome can be likened to the proverbial canary in a coalmine and act as indicators of environmental change. Despite their important function, our understanding of marine microbes and their dynamic behavior remains rudimentary due to the high cost of sampling using traditional oceanographic vessels. This has limited the acquisition of the high density spatial and temporal data needed to develop dynamic predictive models and ruled out sampling remote habitats which are often necessary for establishing baseline 'pristine habitat' data.

To overcome this data gap *Indigo V Expeditions* (IVE), a non-profit organization created by a consortium of scientists, institutions and research centers, developed cost-effective solutions to the sampling challenge by focusing on the advancement of citizen oceanography. The combination of the team's sailboat, *Indigo V*, improvements in sampling technology, and a fleet of volunteer open ocean cruisers are helping researchers understand the world's oceans in a holistic and comprehensive way.

There are thousands of manned vessels cruising the world's oceans every day. Most follow long-established routes dictated by predominant weather and global wind patterns (i.e., the trade winds). These routes often cover tracts of ocean undersampled by traditional oceanographic cruises (Jeffries et al., 2015). IVE puts reliable and sustainable data collection tools into the hands of blue water cruisers, transforming ordinary yachts into *in situ* marine microbe monitoring platforms. Sailors are inherently concerned about the state of the ocean. Equipped with proprietary instrumentation, citizen sailing oceanographers provide the opportunity to collect robust data sets on a scale and under weather conditions never before possible, and in difficult-to-access remote locations (**Figure 1**). There are also the added advantages of drastically reduced sample collection costs compared to traditional oceanographic sampling and reduced carbon footprint associated with data collection (Lauro et al., 2014; Jeffries et al., 2015). With a coordinated approach, these sailors can contribute to unprecedented advances in the field of ocean health and significantly broaden the scope of existing knowledge.

Technological Advancement of Data Gathering and Sharing Methods

Indigo V Expeditions volunteers take chemical measurements of seawater and physically collect water samples that get sent to a laboratory for metagenomics analysis using DNA sequencing. Metagenomics provides a signature of which species of microorganisms are present and their ecological function. Results of the genomic analysis are added to existing baseline information that is used to monitor change and generate signatures of ecological impact (**Figure 2**). In particular, network analysis allows the interactions between microorganisms and

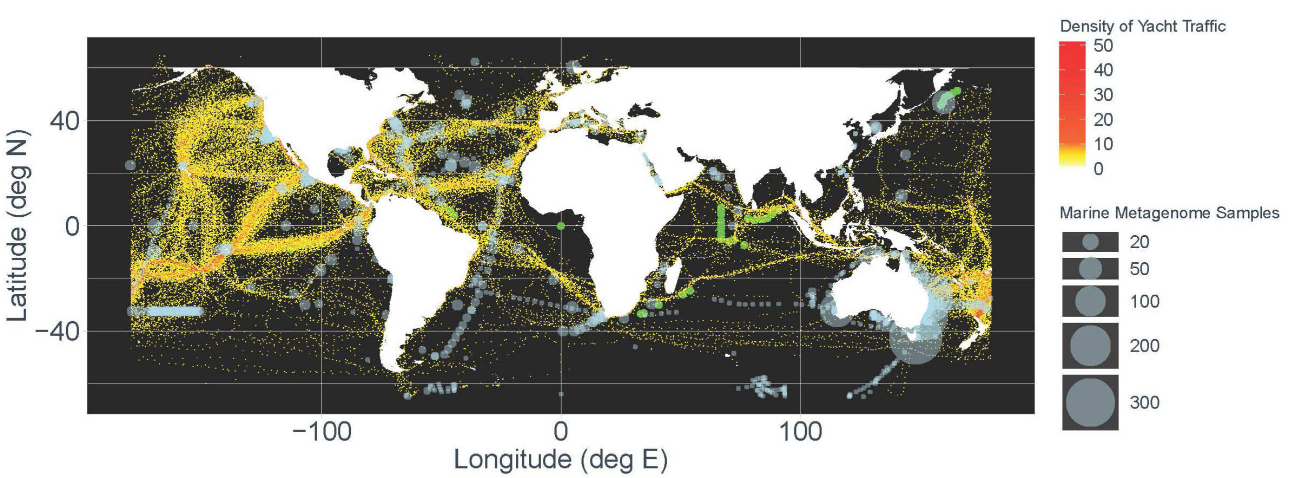

FIGURE 1 | The global map shows the current distribution and sample density of marine metagenomic samples highlighted in light blue (data sourced from the National Center for Biotechnology Information Sequence Read Archive), overlaid by a density plot of waypoints recorded for cruising yachts mapped by YOTREPS during the period 1999–2014. Metagenomics samples gathered by citizen scientists for IVE are highlighted in green.

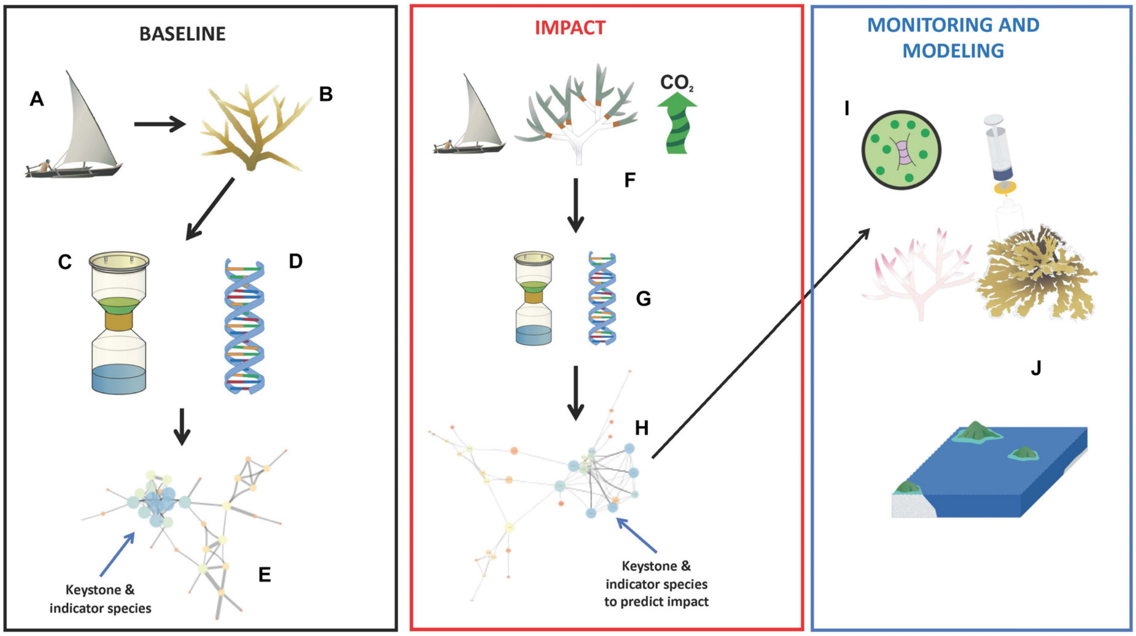

FIGURE 2 | Workflow for citizen science driven monitoring of ocean health using microbes. Citizen oceanographers **(A)** sample ocean habitats, represented here by a healthy coral **(B)**. Microbes are harvested from seawater on a filter **(C)** which then undergoes metagenomic sequencing **(D)** to profile the abundance of microbial species. This data is converted into a network analysis **(E)** which allows high-resolution metrics of microbial diversity and determines "keystone" species indicative of the baseline habitat at the time of sampling. Further sampling following ecosystem impacts **(F)** and replicated sample processing **(G)** allow robust comparison of changing microbiota **(H)** relative to the baseline. Specific organisms indicative of ecosystem change can then be further monitored using cheaper and simpler tools **(I)** to model ocean health **(J)**. *Images courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/)*.

their environment to be visualized and signatures of ecological resilience generated (Bissett et al., 2013). Also, these analyses are capable of identifying "keystone species"; organisms that are highly connected and central to the network structure (Banerjee et al., 2018). These organisms make ideal targets for microbiome engineering and as tools to rapidly monitor ecosystem health. Most recently, microbes that colonize plastics have been collected and sequenced. The microbiome signature on individual fragments of plastic could provide a novel tool enabling researchers to trace back to the origin of the marine plastic.

Volunteer Training and Testing

Citizen sailing volunteers start the process by signing up on the IVE website[1]. They read through program protocols that provide directions on the parameters to be collected/measured. These include plankton sample collection and preservation, temperature and salinity measurements, making sea state observations, and recording location. Participants are then sent either an automated or handheld water collection device. IVE team members Skype with volunteers before and during their excursions to provide comprehensive support before and during their time sampling. Social media is used to communicate information about the voyages to the wider public.

[1]http://www.indigovexpeditions.org/

Results Through Robust Quality Assurance/Quality Control of Volunteer Data

Calibration and Standardization of Equipment

Following each cruise, equipment is sanitized by the volunteers before being sent back with samples to IVE headquarters. Upon arrival, equipment is subjected to thorough decontamination and calibration protocols, and samples are processed and analyzed. The additional decontamination step upon return of the equipment is more thorough than the sanitation performed by citizen scientists and minimizes the risk of cross contamination of invasive species between subsequent uses.

Validation Methods by Expert Marine Scientists

The advisory board of IVE consists of leading experts in the study of the marine microbiome who regularly sail on the organization's yacht. To date, five coastal passages and three long distance ocean crossings have been completed. Key partnerships with oceangoing organizations around the world (e.g., SeaMester and SeaTrek Bali) provide opportunities for temporally intensive data collection in key areas of the ocean, and independent validation of equipment and protocols. While at sea, the team develops and tests the design of their auto-sampling device to standardize collection techniques and establish protocols aimed at reducing sampling variability. Results will be published in peer-reviewed journals and presented at international science conferences.

Accounting for Random Error and Systematic Bias

Due to the high number of samples collected and multidimensional statistics employed in data analysis, bias and error are incorporated into the core statistical workflows, for example, generating random null data distributions to assess the significance of patterns observed. Additionally, for many habitats, professional scientists collect samples to ground-truth collection methods. IVE has conducted three transects of the Indian Ocean to validate community patterns.

Replication Across Volunteers

To date, more than 1,000 samples have been collected. Because the routes of sailors are generally consistent with predominant winds and currents, many of the samples are replicated by volunteers over the course of their travels (**Figure 3**). Thus, collectively the information constitutes long-term data series from which baseline conditions can be established and the effects of climate change and anthropogenic disturbances on the marine microbiome measured. Lauro et al. (2014) estimate that these samples were acquired at a cost that is approximately 20 times less expensive than traditional methods using oceanographic vessels. Ocean sailing races (e.g., Clipper Race, Ocean Race, Vendée Globe, and Mini Transat) should also be regarded as unprecedented resources for the future of microbial ocean observations. By equipping each racing yacht with sampling devices, multiple independent replicate samples may be collected across the same transect. An additional benefit is that modern racing yachts travel at speeds in excess of 30 knots. Equivalent to three times the cruising speed of an oceanographic vessel, temporal confounding effects on the analysis of the spatial biogeography of the microbes can be minimized.

Project Summary

Citizen oceanographers are making important contributions to our understanding of the marine microbiome and its relationship with ecosystem health, climate change and food security. Examples from IVE's approach support the growing need to engage networks of volunteer citizen scientists in research, especially when the topics of interest involve spatial and temporal sampling challenges. Results from this study demonstrate that engaging the public is a win–win for all: positive media attention for sailors; reduced data gaps and access to unique habitats for scientists, and increased awareness about current and emerging ocean threats that are of global significance. The citizen oceanography approach has multiple ramifications. An engaged public focusing on marine microbe data collection will become informed of the environmentally induced changes at the microbiome level and more likely to advocate for changes at the governance level and with their public and private corporate leaders.

Just as the public benefits from increased understanding of the marine microbiome and implications for ocean health, so too will policy and decision makers have to consider allocating resources to mitigate the effects of environmental change. The emergent threats and risks related to maritime security, coastal infrastructure, food supply, and tourism can be identified from ocean and marine microbe analyses. Public projects can then be resourced to address each of these potential risks and help implement solutions. We envision that in the future, other networks of volunteer citizen scientists could be mobilized to focus on solutions for any of these priorities.

FIGURE 3 | Fishing boats such as these can be used to help map the ocean floor. Image courtesy of NOAA.

EXAMPLE 3: ENCOURAGING INNOVATIVE SUPPLEMENTARY DATA GATHERING: AN INTERNATIONAL HYDROGRAPHIC ORGANIZATION CROWDSOURCED BATHYMETRY INITIATIVE

Project Introduction

Bathymetry, defined as the depth and shape of the seafloor, underpins the safe, sustainable, cost effective execution of nearly every human activity at sea. Yet, most of the seafloor remains unmapped and unexplored. Less than 18% of the oceans have been directly measured (Mayer et al., 2018). The vast majority of the data used to compile seafloor maps are estimated depths derived from satellite gravity measurements. These data can miss significant features and provide only course-resolution depictions of the largest seamounts, ridges and canyons. Progress in mapping coastal waters is only marginally better. International Hydrographic Organization (IHO) publication *C-55, Status of Surveying and Charting Worldwide*, indicates that about 50% of the world's coastal waters shallower than 200 m have not been surveyed. Ongoing collaborative mapping efforts, both global [e.g., IHO, General Bathymetric Chart of the Ocean (GEBCO), Seabed 2030] and regional [e.g., the Atlantic Ocean through the Atlantic Ocean Research Alliance (AORA) and the Galway Statement] are underway to improve this situation but remain vastly under-resourced.

The IHO has a history of encouraging innovative ways to gather data and data maximizing initiatives so that we can better understand 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 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). The information would be used to supplement the more rigorous and scientific bathymetric coverage done by hydrographic offices, industry, and researchers around the world.

While CSB data may not meet accuracy requirements for charting areas of critical under-keel clearance, it does hold limitless potential for myriad other uses. If vessels collect and donate depth information while on passage, the data can be used to identify uncharted features, assist in verifying charted information, and to help confirm that existing charts are appropriate for the latest traffic patterns. This is especially relevant considering that many soundings on charting products are pre-1950. In some cases, CSB data can fill gaps where bathymetric data are scarce, such as unexplored areas of polar regions, around developing maritime nations, and the open ocean. CSB also has potential uses along shallow, complex coastlines that are difficult for traditional survey vessels to access. These areas may be more frequently visited by recreational boaters whose data could help illustrate seafloor and shoaling trends from the repeated trips they make along their favorite routes. CSB will also be invaluable in providing ground-truthing data to validate Satellite Derived Bathymetry (SDB). SDB is a necessary technology in the Arctic yet has a serious validation problem irrespective of the model (empirical, semi-empirical, or physics). Finally, crowdsourced bathymetry can provide vital information to support national and regional development activities and scientific studies in areas where little or no other data exists.

Approach/Methods

The key to successful CSB efforts is volunteer observers who operate vessels-of-opportunity in places where charts are poor or where the seafloor is changeable and hydrographic assets are not readily available (**Figure 3**). The International Convention for the Safety of Life at Sea (SOLAS) 1974 carriage requirements oblige all commercial vessels to be equipped with certified echo-sounders and satellite-based navigation systems. As a result, the world's commercial fleet represents a significant, untapped source of potential depth measurements. Even most non-commercial ships and boats are equipped to measure and digitally record their depth in coastal waters and an ever-increasing number of vessels can also take measurements in deeper water. The CSB vision is to tap into volunteer enthusiasm for mapping the ocean floor. Enabling trusted mariners to easily contribute data will augment current bathymetric coverage and enhance charting capabilities of the bathymetric initiative.

Technological Advancement of Data Gathering and Sharing Methods

Under the guidance of the IHO Crowdsourced Bathymetry Working Group (CSBWG), the National Oceanic and Atmospheric Administration (NOAA) has been working over the last few years to provide archiving, discovery, display and retrieval of global crowdsourced bathymetry data contributed from mariners around the world. These data reside in the IHO's Data Centre for Digital Bathymetry (DCDB), hosted by NOAA's National Centers for Environmental Information (NCEI), which also offers access to archives of oceanic, atmospheric, geophysical, and coastal data (**Figure 4**).

Crowdsourced bathymetry enters the DCDB through a variety of trusted sources or nodes (e.g., partner organizations, companies, and non-profit groups) that enable mariners to voluntarily contribute seafloor depths measured from their vessels. Rose Point Navigation Systems, a provider of marine navigation software, helped kick start the stream of data from a crowd of mariners. Specifically, users of their software were given the option to enable logging of their position, time and depth. Users were then given the choice to submit their data anonymously or provide additional information (vessel or instrument configuration) to enrich their dataset. Rose Point then collates the observations and submits them to the IHO DCDB where anyone can access the data for commercial, scientific, or personal use.

The intent is that these data, like all bathymetric data submitted to the DCDB, would not necessarily be "harmonized" or reviewed but would reside in the DCDB "as is." It would remain up to the end users to determine their value and utility for their own purpose. In this way, the fundamental data that reside in the DCDB will serve as the world reference raw bathymetric data set which can be used as the basis for refined and processed products.

Volunteer Guidance

The IHO CSBWG, comprised of international scientific, hydrographic and industry experts, was tasked by the IHO to draft a guidance document meant to empower mariners to map the gaps in the bathymetric coverage of the world's ocean. This document 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 crowdsourced bathymetry. The document will become an adopted IHO publication on crowdsourced bathymetry in early 2019. The working group is now focused 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.

Early Results

The crowdsourced bathymetry database currently contains more than 117 million points of depth data. These have been used by hydrographers and cartographers to improve nautical chart products and our knowledge of the seafloor. Two early testers of the data are the hydrographic offices at NOAA and the Canadian Hydrographic Service.

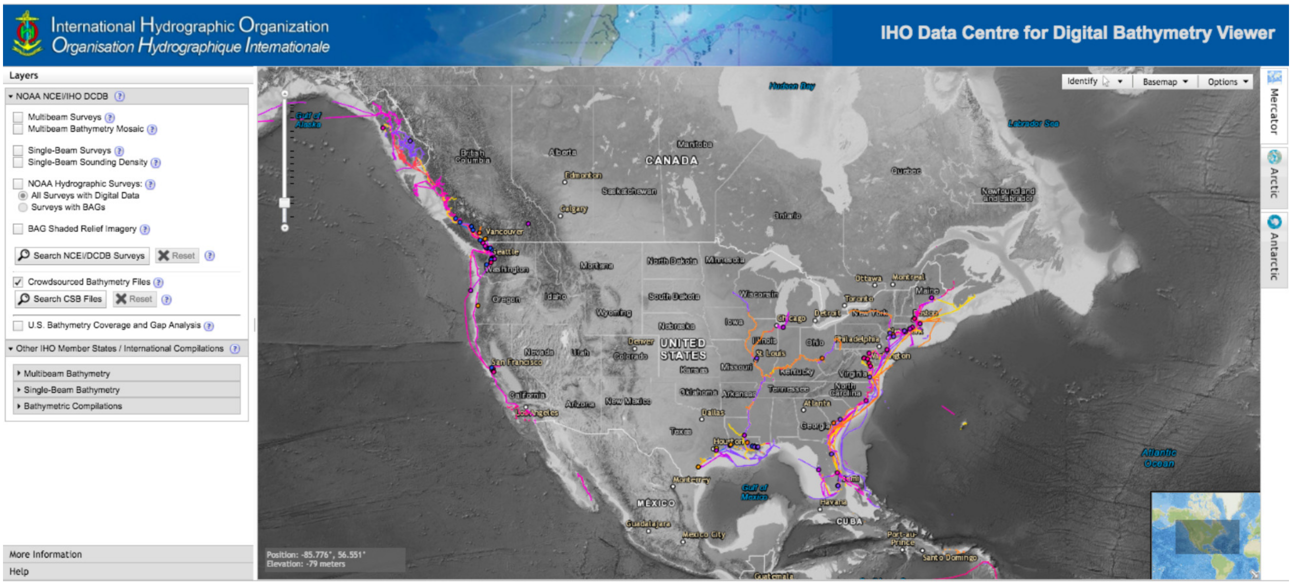

FIGURE 4 | The IHO DCDB Bathymetry viewer displays various bathymetric data holdings (including crowdsourced bathymetry ship track lines, shown here in purple/pink) from NOAA NCEI and other repositories to support international seafloor mapping efforts.

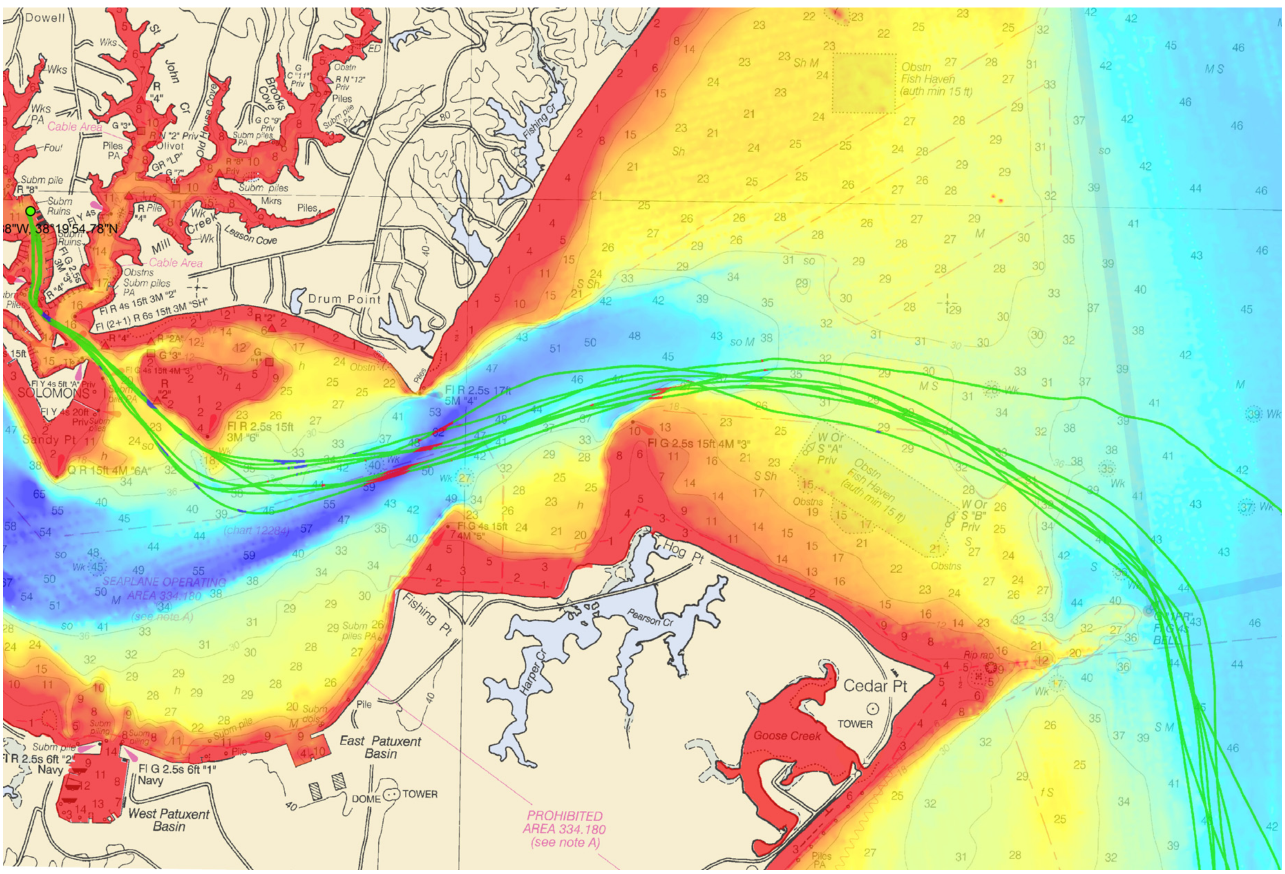

FIGURE 5 | NOAA's *Bay Hydro II* crowdsourced bathymetry test tracks in green overlaid on multibeam survey data demonstrates how changes can be detected. Image courtesy of NOAA.

Case Study #1: NOAA Chart Adequacy Assessment

NOAA, in partnership with George Mason University, is using the crowdsourced depths submitted to the database to assess the adequacy of its nautical chart products. Comparing mariner-supplied crowdsourced bathymetry against existing charted depths and survey data, NOAA can determine when areas require updated survey information and identify chart discrepancies before an incident occurs (**Figure 5**). The information is particularly important in areas where the bottom shifts frequently. Additionally, crowdsourced bathymetry measurements over well-trafficked or repeated routes can provide a time series to better refine survey planning for different areas and harbors. This information allows NOAA to better prioritize and plan survey operations and maintain nautical charts.

Chart adequacy assessments have proven to be a valuable tool for using similar publicly available data sources such as Satellite Derived Bathymetry to enhance the quality of NOAA's cartographic products. These assessments can provide valuable and timely information in situations of immediate need, such as disaster response. More information on chart adequacy assessments using non-survey bathymetry data can be found in collaborative publications with both the University of New Hampshire's Center for Coastal and Ocean Mapping and GEBCO.

Case Study #2: Canadian Hydrographic Service: Inside Passage

The Canadian Hydrographic Service (CHS) has used this dataset to update several Inside Passage charts along the coastal routes stretching from Seattle, Washington, to Juneau, Alaska. The data were downloaded and easily converted into CHS formats. A systematic comparison of charted depths less than 10 m yielded improved charted channel depths, data density and improved chart compilation in areas that were surveyed with singlebeam. CSB helped prioritize survey areas for the following survey season and initiated the publication of Notices to Mariners.

Project Summary

The IHO invites more maritime companies to support crowdsourcing efforts by making it simple for their customers to participate using their navigational systems. For example, Rose Point Navigation Systems further promoted the IHO crowdsourced bathymetry initiative by moving the option to collect and contribute bathymetry data to a more visible section of its program options menu. Crowdsourced efforts and the crowdsourced bathymetry database are poised to become a major source of information. They are not only improving nautical chart coverage and accuracy, but contributing to international mapping efforts such as Seabed 2030. These data have the potential to become critical resources for coastal zone management and environmental and scientific studies, particularly in areas of little perceived commercial or strategic value.

EXAMPLE 4: 50,000 CITIZEN-SCIENCE COLLECTED GPS FLOOD EXTENTS USED TO VALIDATE A STREET-LEVEL HYDRODYNAMIC MODEL FORECAST OF THE 2017 KING TIDE IN HAMPTON ROADS, VA

Project Introduction

The rate of sea level rise in Hampton Roads, VA, is primarily dictated by polar ice melting, local land subsidence, and the relative strength of the Gulf Stream current. Combined, these interact to influence the extent of inundation under different circumstances. *Catch the King Tide* was the world's largest simultaneous citizen-science GPS data collection effort to document the extent of flooding during a king tide. These higher than normal tides typically occur during a new or full moon and when the Moon is at its perigee. More than 700 volunteers mapped the king tide's maximum flood extent to validate and improve predictive models and future forecasting of increasingly pervasive nuisance flooding. 59,006 high water marks and 1200+ geotagged pictures of inundation were captured using the 'Sea Level Rise' mobile app to trace the shape of the floodwaters using GPS location services. Heavily promoted by the local news media, citizen engagement during the inundation event was high, resulting in an average of 572 GPS-reported high water marks per minute during the hour surrounding the king tide's peak, observed at 9:32 am local time on November 5, 2017, in Hampton Roads, VA.

Tidewatch is a tidal prediction system developed by the Virginia Institute of Marine Science (VIMS) which provides forecasts for 12 sites throughout Chesapeake Bay. Since then, the predictions have expanded to include 18 new sensors installed by the United States Geological Survey (USGS) in 2016 and 28 new stations installed by the StormSense Smart Cities Initiative in 2017–2018 throughout Hampton Roads prior to the 2017 king tide (Rogers et al., 2017). An interactive map of the new gauges was superposed with VIMS' tidal inundation predictions before the flood event to inform volunteers where flooding was predicted to occur in public spaces, and then the map was populated in near-real time with the GPS-reported high water marks as they were retrieved from the Sea Level Rise App. The map for 2017's Catch the King tide event can be viewed at: http://bit.ly/2zcS7Ba, and the predictions and data for the 2018 king tide on October 27 are available at: https://bit.ly/2QCLwF0.

Technological Advancement of Data Gathering and Sharing Methods

Each year, prior to the king tide flood event, Dr. Derek Loftis at the VA Commonwealth Center for Recurrent Flooding Resiliency (CCRFR) designs a web map to direct volunteers to public places that are forecasted to flood during the King Tide using VIMS' hydrodynamic models. An interactive story map with geospatial tidal flood forecasts for the king tide was embedded in digital versions of print media articles of local media groups for 10 weeks leading up to the king tide monitoring event in 2017.

This engagement tool was invaluable, and was connected with the Sea Level Rise free-to-use mobile app, and Facebook, which in conjunction with the constant support of the event's media partners, reached over 10,000 page views before the 2017 King Tide in less than 3 months after launch: http://www.vims.edu/people/loftis_jd/Catch%20the%20King/index.php.

Then, during the king tide, time-stamped GPS data points along the floodwater's edge were collected by many trained volunteers to effectively breadcrumb/trace the high water line. Subsequently, these points were used to verify the accuracy of the tidal flood predictions from the Tidewatch Coastal Inundation Model. This effort for predicting tidal flooding can be mapped using multiple methods (which were all used in 2017 and 2018):

(A) A simple bathtub model using topographic elevations corresponding to current or forecasted water levels at a nearby water level sensor (Loftis et al., 2013, 2015).
(B) A street-level hydrodynamic model fed atmospheric and open boundary tidal and prevailing ocean current inputs from large scale models translated to the street level via computationally efficient non-linear solvers (Wang et al., 2014) and semi-implicit numerical formulations (Loftis et al., 2016) aided by a sub-grid geometric mesh (Steinhilber et al., 2016) with embedded Lidar data (Boon et al., 2018).
(C) Interpolated measurements from densely-populated mesh networks of water level sensors advised by artificial intelligence and real-time data assimilation, such as StormSense (Loftis et al., 2018).

Volunteer Training and Testing

The volunteer coordination effort involved a hierarchical scheme led by an adept volunteer coordinator from the Chesapeake Bay Foundation. Qaren Jacklich has successfully led the "Clean the Bay Day" litter collection initiative in Chesapeake Bay for several years prior to Catch the King, and without her interaction with each of the hundreds of registered volunteers, there would be far less tidal flooding data. Working below Qaren, the volunteer coordinator, were over 120 volunteer "Tide Captains" who led smaller groups of volunteers in their flood-prone subdivisions, neighborhoods, and communities (**Figure 6**). In many cases, these tide captains were knowledgeable, trained teachers, and enthusiastic users of the Sea Level Rise mobile app. They trained neighbors, friends and children in their communities at more than 35 separate volunteer training events held all over Hampton Roads' spanning 12 major cities and counties in 2017. In 2018, 42 training events were offered.

Approximately 45% of the 722 registered volunteers attended an outdoor formal training session on how to use the Sea Level Rise mobile app to document active flooding. This approach was used in 2017 to map the flooding extents across 12 coastal cities and counties in Virginia by pressing the 'Save Data' button in the 'Sea Level Rise' App every few steps along the water's edge during the high tide on the morning of November 5th, 2017, and October 27, 2018 (**Figure 6A**). The Sea Level Rise mobile app is capable of taking field notes and uploading time-stamped, geotagged pictures and recording accurate location history for mapping tidal flooding. The mobile app is also innovative in that the quality assurance mechanism is inherently hierarchical, allowing the event coordinator to limit participation to certain registered users and filter data permissions such as photo uploads and GPS data collection to only certain trained users. Event managers can download their data as.csv files after the specified time window for their flood monitoring event has closed, and even retroactively remove volunteers that consistently measured erroneous data points. The resulting maps shown in the next section represent dense areas of flood extent data areas surveyed during the event (**Figure 6B**), followed by lessons learned.

Results Through Robust Quality Assurance/Quality Control of Volunteer Data

Calibration and Standardization of Equipment

People attended a sea level rise app training event in a parking lot near the waterfront. They learned how to make notes, take pictures, and breadcrumb their path along transects. They worked in the parking lot and along the high tide line on a waterfront to calibrate their phones and for the reference of the scientists who can later review their user number to best interpret their results (**Figure 7**). Inevitably, the app performance and relative GPS accuracy is different across the iOS and Android platforms and is even more dependent upon the hardware of the many different models in the repertoire of each vendor on these platforms. For example, some older phone models don't use enhanced GPS, location from satellites, nearby cell towers, or nearby WiFi gateways with geolocation while some of the latest models have multiple antennae and can triangulate a user's phone in the repertoire of each vendor on these platforms.

With such a disparity of technologies across a monitoring group, a radial accuracy error metric (in m) was recorded for each measurement to inform scientists of a circular envelope of possible user locations for each measurement (Loftis et al., 2016). These locational accuracies are the first filtering metric when reviewing data. Anything greater than 5 m error was filtered out for validation. This removed approximately 2.8% of all recorded measurements during the 2017 Catch the King.

Validation Methods by Expert Marine Scientists

Field-collected pictures, notes and flood extents are submitted through the Sea Level Rise Mobile application and are time-stamped and stored digitally at the searisingsolutions.com website. Data and metadata are simultaneously entered into a Microsoft Excel database by the app and interpreted by data scientists and data-certified volunteer coordinators who are registered as managers within each flood mapping region, to check for quality assurance. The GPS data are then filtered into geo-tagged photos and GPS points. The photos are used to reference inundated landmarks with survey monuments nearby to interpret depths against the USGS topobathymetric 1-m resolution Digital Elevation Model for the Chesapeake Bay (Danielson et al., 2016).

The GPS data points without attached photos are used to compare with contour data for the bathtub tidal prediction models and interpret slope of water throughout the river and bay

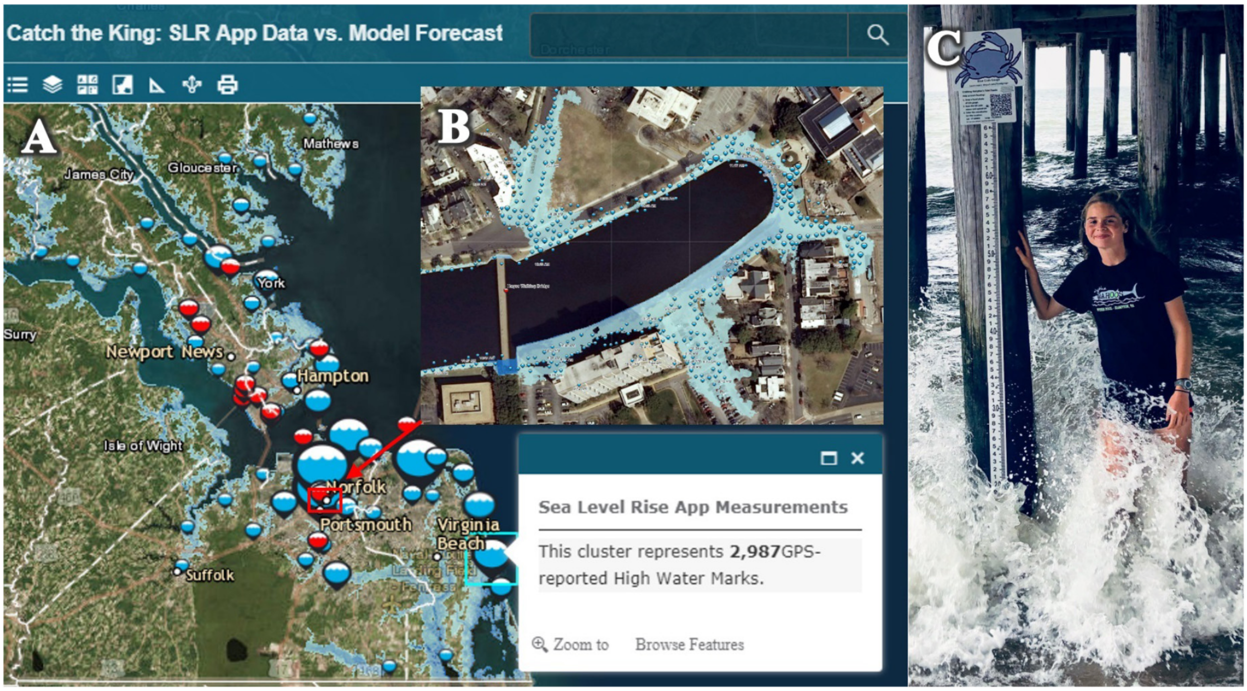

FIGURE 6 | (A) Web map of king tide inundation extent data collection on 11/5/2017. http://arcg.is/1HLOPS. **(B)** Inset: zoom of Norfolk's historic Hague depicting a zoomed map of the area with dense patches of volunteer-observed flood extents noted with timestamped blue dots, and model-predicted tidal flood extents in light blue. **(C)** Student scientists photograph flood gauges during tidal inundation events and scan a QR code to upload their images via a geoform or the Sea Level Rise App to aid in validating flood depths. Photo credit: Derek Loftis.

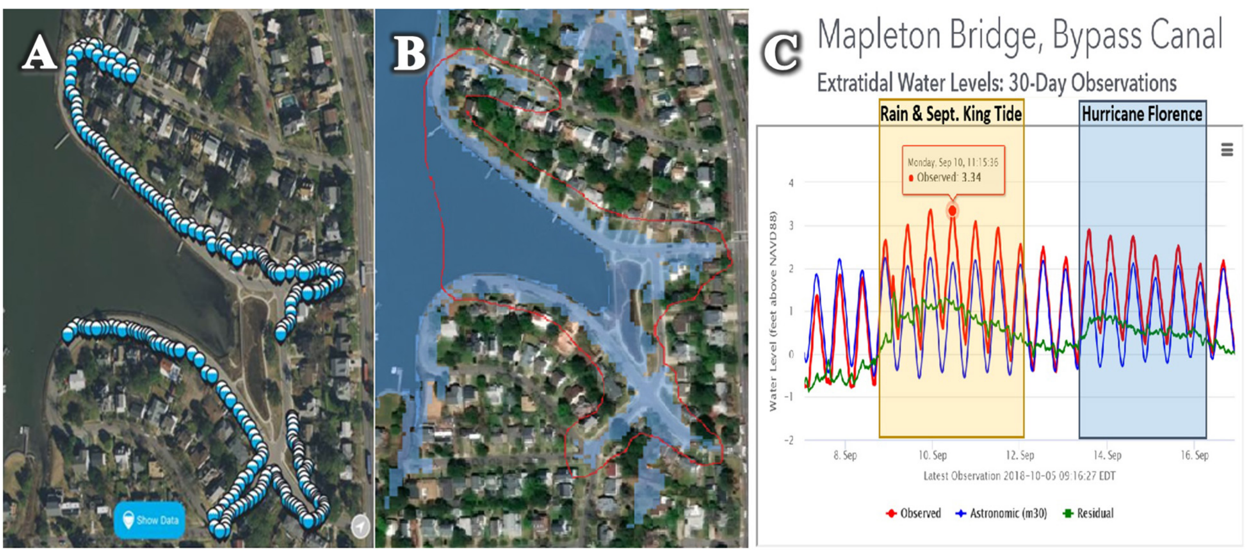

FIGURE 7 | (A) Sea Level Rise Mobile App GPS data compared with **(B)** Tidewatch geospatial inundation forecast at 11:15 am local time on September 10, 2018, in Larchmont, Norfolk, VA, after **(C)** 6 inch of rainfall concomitant with the Sept. King Tide was detected at a nearby weather station just 4 days prior to the arrival of 2018 Hurricane Florence.

basins. This is especially important if there is significant wind concomitant with a king tide. The GPS data are then enhanced with the Lidar elevations from the USGS DEM and filtered to remove any areas greater than 3 feet above the maximum observed tidal water level at any of the nearby water level sensors (5 feet for storm surge). The true benefits of mapping a king tide are to have a record of highest astronomical tidal extents in a region over time, while simultaneously educating volunteers of their flood risk, and validating and improving flood models. Adding value to this, volunteers now know how to map flooding in their community and can use low-stakes flood events like a king tide as an opportunistic dress rehearsal to learn how to accurately map inundation before more significant events like 2018 Hurricane Florence (**Figure 7**). In more severe cases, once volunteers are safely comfortable that adverse conditions have passed, inundation markers such as debris lines are recorded similar to USGS file reports (but with less sophisticated surveying equipment) to capture flood features that are likely to be removed before official survey crews come by to document the event more than 24 h later.

In addition to the flood extent monitoring effort through the Sea Level Rise App, some communities have engaged middle school and high school students in characterizing the flood in terms of depths. Since mobile phones currently do not have exceptionally accurate altitude sensors, the GPS breadcrumbs of tidal extents are converted to inundation contours to interpret relative depths from Lidar-derived digital elevation models for vertical comparison with VIMS' street-level models. While these DEMs are the same as those implemented in the hydrodynamic flood forecast models, recent Lidar elevations are needed to accurately assess depths throughout the region, and most Lidar surveys used in Hampton Roads are nearly 5 years old. As subsidence in the region has been observed to be inhomogeneous (Bekaert et al., 2017), assumptions of these elevations being accurate as appended to the Volunteer data based upon GPS location is questionable. Thus, implementing flood depth gauges in frequently flooded areas that volunteers can photograph near surveyed landmarks has been a key factor in assuring quality citizen-science data through Catch the King. Thus, student projects in the region have recently centered around closing this gap to allow people to learn more about local sea level rise for a relatively low cost. One such project consists of six flood-monitoring gauges around the city at which everyday citizens or "citizen-scientists" input the altitude measurements of flooding. Getting school groups involved in this research has been a central component in making Catch the King a year-round tide mapping and education initiative.

The filtered and vertically validated data are then compared using each citizen-observed point and comparing them to the predicted maximum flood extent raster as a geospatial predictive accuracy metric of mean horizontal distance difference in m, similar to Steinhilber et al. (2016). Water levels were compared with nearby water level gauges to estimate depths relative to a root mean squared error in cm.

Project Summary

The new water level sensor data and the crowd-sourced high water marks from the king tide were initially filtered for relative location accuracy and timing, interpolated with the use of digital elevation models to define estimated flood depths. This was subsequently compared with elevation contours to develop a difference map to identify areas where VIMS' water level predictions through Tidewatch and via their street-level hydrodynamic model over-predicted and under-predicted flooding during the king tide. A geostatistical comparison between the model's maximum inundation extents and the volunteers' GPS observations yielded a mean horizontal distance difference of 19.3 feet (5.9 m). Vertical accuracy of the flood model's predictions during the king tide were determined via comparison with 42 water level sensors to be within a root mean squared error of 1.4 inch (3.5 cm).

EXAMPLE 5: CITIZEN SCIENTISTS: AN UNDERUTILIZED RESOURCE FOR THE UNITED STATES IOOS

Project Introduction

The Gulf of Mexico Coastal Ocean Observing System (GCOOS) is the United States Integrated Ocean Observing System (IOOS) dedicated to the Gulf of Mexico (GoM). Actions of the organization support four focus areas and three cross-cutting themes identified in the Strategic Plan[2]. Focus areas include Marine Operations, Coastal Hazards, Healthy Ecosystems and Living Resources, and Human Health and Safety. The cross-cutting themes include Outreach and Education, Data Management and Communication, Numerical Modeling and Forecasting and Monitoring Long-term Environmental Change. Historically, as stakeholder products and services have been identified and developed, companion outreach and educational resources have been created (Simoniello et al., 2015).

The Gulf Citizen Science Portal (GCSP) described here has been structured to accommodate data and information acquired by volunteer monitoring networks throughout the GoM region. The information provided is complementary to data being served on the GCOOS Hypoxia Nutrient (H-N) Data Portal. Developed with support from the Gulf of Mexico Alliance, water quality-related information from approximately 80 organizations is aggregated in the H-N portal as a one-stop shop for Gulf resource managers[3]. The portal supports informed strategies needed to reduce nutrient inputs and hypoxia impacts. Covering the inshore waters of estuaries to the continental shelf break of the five United States Gulf states, users can inspect base maps of observations down to the station level.

The GCSP[4] was built as the outreach and education component of the GCOOS H-N Data Portal. Gulf-wide, hundreds of grassroots groups monitor environmental conditions in their local areas. Often that information is not shared with management agencies or organizations that could make real-world use of it. One reason is that few organizations have the capabilities to handle the challenges inherent in integrating diverse datasets collected with different methodologies and instrumentation. GCOOS piloted the portal with two partner organizations as a cost-effective way to support cross-regional water quality collaborations (**Figure 8**). The goal was to create meaningful educational opportunities while at the

[2] https://issuu.com/gcoos-ra/docs/gcoos-stratplan-and-addendum
[3] https://nutrients.gcoos.org/
[4] http://gulfcitizenscience.org/

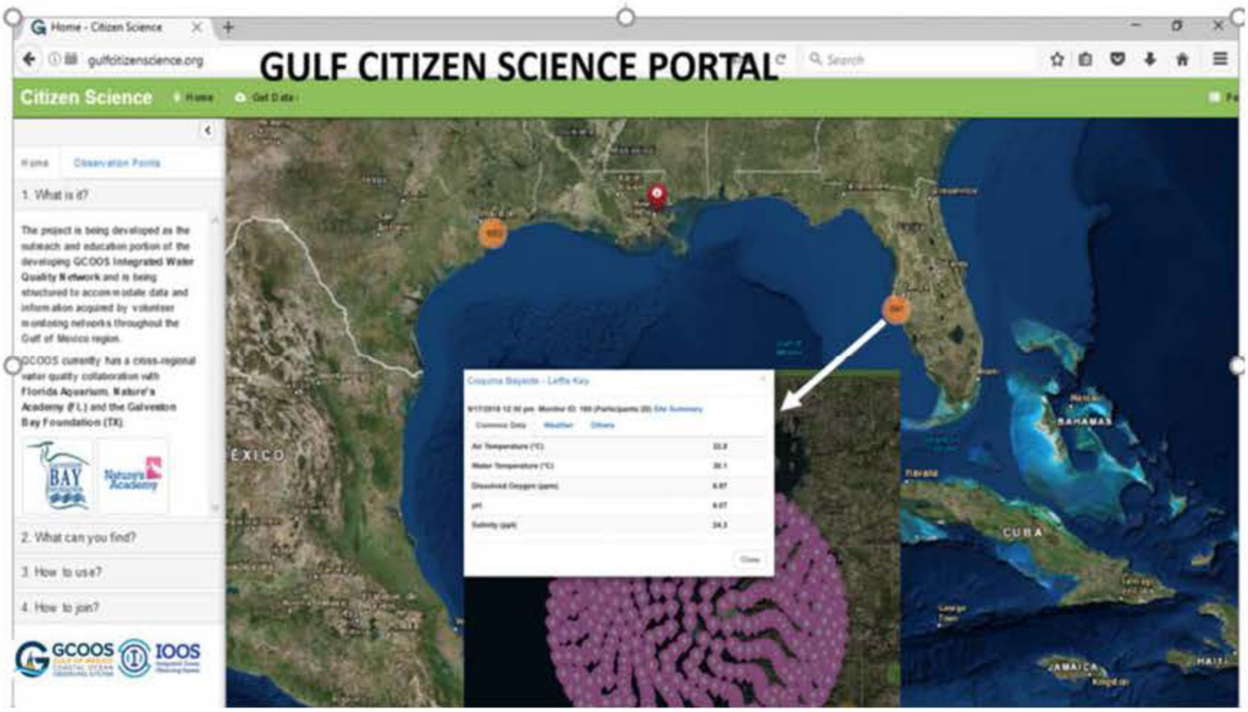

FIGURE 8 | The Gulf Citizen Science Portal, with inset showing expanded view of data—air and water temperature, dissolved oxygen, pH and salinity, available at one station (Leffis Key, FL).

FIGURE 9 | Galveston Bay Foundation's Water Monitoring Team volunteers collect monthly water quality data from sites around Galveston Bay **(Left)**. Nature's Academy participants conduct biodiversity assessments as part of their outdoor education curriculum **(Right)**. Photo credits: GBFWMT **(Left)** and Chris Simoniello **(Right)**.

same time allowing state, federal and academic programs to supplement datasets with important detail.

Volunteer Training and Testing

The integration of volunteer-collected metocean, water quality, biodiversity and marine debris data was developed in partnership with the Galveston Bay Foundation, Texas, and Nature's Academy, Florida. Both non-profit programs were leading ongoing monitoring of a variety of environmental parameters but lacked sufficient data sharing methods. The Galveston Bay Foundation's Water Monitoring Team (GBFWMT) is a citizen science initiative that trains volunteers to collect monthly water quality data from specific near-shore sites around Galveston Bay (**Figure 9**). For the past 6 years, 60 trained volunteers have monitored 60 sites around the Bay. Natures Academy offers a variety of STEM-focused and stewardship education programs. Launched in 2007, most of their 65,000 plus participants have engaged in water quality, biodiversity and marine debris-related data collection. Participation in Nature's Academy programs is diverse and includes local underserved youth and groups from 42 states and five countries (**Figure 9**).

Each organization collects meteorological and estuarine/coastal ocean data based on their priorities and objectives. Common parameters are air and water temperature, wind speed and direction, barometric pressure, relative humidity, dissolved oxygen, pH, and salinity. Other parameters include nutrients, turbidity, specific gravity, precipitation, surface algae coverage, water color, sea state, and tidal cycle. Nature's Academy provides data on the abundance and composition of beach litter, and on biodiversity, reporting the number of species collected, including most abundant species.

Approximately 50% of the GBFWMT is certified to collect fecal indicator bacteria data (e.g., *Enterococcus*). Training includes proper bacteriological sampling, transport and laboratory techniques following protocols established by the Texas Commission on Environmental Quality (TCEQ, 2012). Levels are used to determine if a given site is suitable for recreational use. The information supplements monitoring by local research institutions and state agencies which lack the capacity to regularly monitor both water quality and bacteria throughout the bay. Galveston Bay has a large number of diverse users spread along its shoreline and there is a high demand for localized information. The monitoring team not only helps meet this demand for localized water quality data but empowers residents at these locations by engaging them in the sampling and interpretation processes on a voluntary basis. In addition to training for sampling bacteria, volunteer monitors follow the certification system developed by the Texas Stream Team. The training includes practical experience in field techniques, quality assurance and data management (Texas Stream Team [TST], 2009). Procedures and requirements have also been established to become certified Texas Stream Team trainers and Quality Assurance Officers (Texas Stream Team [TST], 2014).

Technological Advancement of Data Gathering and Sharing Methods

Both the GBFWMT and Nature's Academy record information in a Microsoft Excel database which gets pushed to the GCSP. Like the H-N portal, users can drill down to inspect base maps of observations at the station level. Work is underway to transition data from the GBFWMT to a relational database in Microsoft Access. The goal is to enhance data extraction and manipulation while better maintaining the integrity of the data and establishing threshold values for each parameter.

Results Through Robust Quality Assurance/Quality Control of Volunteer Data

Calibration and Standardization of Equipment

Nature's Academy, using Pasco Scientific probe ware, and the Galveston Bay Foundation, using YSI instruments, follow similar equipment standardization and calibration regimes. Both use internal program testing and maintenance requirements in combination with guidelines outlined in the manufacturers' manuals (YSI, 2009a,b; PASCO PS-2169 Water Quality Multi Measure Sensor User Manual, 2012). Records are kept on all field and laboratory equipment testing, maintenance and repair schedules. Data not meeting post calibration error limit requirements are flagged in the database for further review by the respective project managers/quality assurance officers.

Validation Methods by Expert Marine Scientists

Field-collected data are recorded on data sheets and/or stored digitally. Data and metadata are subsequently entered into a Microsoft Excel data base by certified volunteer coordinators who check for quality assurance. Each organization stores data internally on company servers, maintains the original data forms, and coordinates with GCOOS to upload information to the GCSP. Basic statistical analysis is conducted to determine random error, systematic bias, and replicability across monitoring locations, volunteers and sampling dates. Subsequent to data upload, companion hands-on lessons are developed and implemented by GCOOS. These are aimed at Science, Technology, Engineering, and Mathematics (STEM) literacy targeting underserved students (Simoniello and Watson, 2018) to make STEM curriculum meaningful (Fraser et al., 2013; Levin and Dickerson, 2015; Dickerson et al., 2016).

Project Summary

Though not a solution for all ocean monitoring needs, Gulf citizen scientists offer compelling examples showcasing their ability to augment and enhance traditional research and monitoring. Information they are providing is increasing the spatial and temporal frequency and duration of sampling, reducing time and labor costs for academic and government monitoring programs, providing hands-on STEM learning related to real-world issues and increasing public awareness and support for the scientific process. Currently, GCOOS GSCP efforts are focused on establishing guidelines and machine-to-machine capabilities for the growing number of volunteer data providers interested in contributing information to the portal. The long-term goal is to establish a nested "system of systems" of citizen scientist-collected information across the national IOOS footprint.

CHALLENGES FOR CITIZEN SCIENCE EFFORTS OF THE FUTURE

While there's a growing body of evidence supporting the contributions of citizen scientists to some of the world's most pressing issues, challenges remain. Some of the more obvious challenges to overcome before wide-scale inclusion in rigorous monitoring programs include quality assurance and quality control limitations, legal/liability and ethical concerns and cyber infrastructure to support data management, discovery, metadata, and security. Less obvious challenges also exist. For example, in coastal settings, it is not always clear where the demarcation is between public and private beaches (O'Hara et al., 2016). Thus, trespassing issues arise. Another potential complication arises if/when local administrators decide it is more economical to replace professional environmentalists with volunteers. In many instances, the solution to resolving a challenge like this is at the crossroads of science and sociology—overcoming the idea that local traditional environmental knowledge can replace rigorous science rather than complement it. Potential for false alarms also needs to be mitigated. The peer review process for scientists provides a system of checks and balances. If volunteers are convinced they've observed something, even if it is an honest error, there could be negative economic or public relations consequences. Numerous bodies like the Open Geospatial Consortium's Citizen Science Interoperability Experiment and the Wilson Center's Citizen Science Association are beginning to tackle these issues. Global efforts across Europe, Canada, the United States and Australia are embarking on initiatives to promote successful expansion of the citizen science field through standardization of metadata, post-collection data processing and other aspects of this growing community.

CONCLUSION

The democratization of ocean observation has the potential to add millions of observations every day. Examples provided here demonstrate the wide range of people who are already dramatically reducing gaps in our global observing network while at the same time providing unique opportunities to meaningfully engage in ocean observing and the research and conservation it supports. Data gaps from the seafloor to the estuaries and from the tropics to the poles are being filled by volunteers who are contributing to safer navigation, community resiliency and understanding of climate impacts on living marine resources. As domestic and international citizen science associations are becoming increasingly organized, the potential for citizen scientists to be part of an effective global strategy for a sustained, multidisciplinary and integrated observing system is closer to being realized.

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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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The Role of Stakeholders in Creating Societal Value From Coastal and Ocean Observations

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The importance of stakeholder engagement in ocean observation and in particular the realization of economic and societal benefits is discussed, introducing a number of overarching principles such as the convergence on common goals, effective communication, co-production of information and knowledge and the need for innovation. A series of case studies examine the role of coordinating frameworks such as the United States' Interagency Ocean Observing System (IOOS®), and the European Ocean Observing System (EOOS), public–private partnerships such as Project Azul and the Coastal Data Information Program (CDIP) and finally the role of the "third" or voluntary sector. The paper explores the value that stakeholder engagement can bring as well as making recommendations for the future.

Keywords: ocean observing systems, stakeholder engagement, case studies, societal benefits, SDG14

INTRODUCTION

Ocean observations, both at and below the sea surface, provide data and information required to underpin assessments, analyses, and predictions of the state of the ocean environment. Ocean observations enable monitoring of ocean climate, provide early warning/tracking of high impact weather and oceanographic events and are used to initialize and verify the performance of forecasting models. The data and information provided by ocean observations, in turn, supports the commercial and industrial sectors (e.g., offshore oil and gas operations, safe and efficient maritime transport, tourism and recreation), and realizes societal benefits such as better management of public health risks and protection of people and property from natural hazards at the coast (Bell et al., 2013; US IOOS, 2018[1]). In addition sustained ocean observations, measurements and models provide an important input to weather forecasts and climate projections, delivering socioeconomic benefits far inland (Rayner et al., 2018).

To fully realize the societal and economic benefits of ocean observation there is a requirement for an integrated ocean observing system. The term integrated ocean observing system describes a network of observation platforms and sensors that acquire a huge variety and volume of spatio-temporal data about the ocean environment. Such an integrated observation system includes activities such as data acquisition, transmission, management, and communications, analyses and modeling. These integrated systems contribute to the information-base which enables the benefits from the blue economy to be maximized.

Stakeholder engagement is a key element of the beneficial use of an integrated ocean observing system. A productive and sustainable ocean economy requires strong partnerships. A diversity of stakeholders – managers, decision-makers, users of ocean observing products and services, socioeconomic communities and civil society, and the builders and operators of observing systems, amongst others – contribute to maximize the economic benefit from the blue economy (Malone et al., 2014). A clear understanding of, and mutual agreement on the role and needs of stakeholders is required to bridge the gap between ocean observations, as an activity born out science and engineering, and its benefits to society. Comprehensive stakeholder engagement helps facilitate the identification of gaps in ocean observing, enhancing derived products and services, and ensuring global capacity and capability exists to enable the use of observation systems and science. However, it is also important to recognize that the various stakeholders have different institutional mandates, objectives, operational and strategic priorities, resources and management procedures.

Ocean observing can be a costly endeavor. Whilst there is no globally accepted figure the European Union (2018) have examined the cost of undertaking ocean observing in a number of European countries and further afield. Capital costs alone can be upward of thousands of million euros per country with associated operational costs in the hundreds of millions per year. It is not unreasonable to expect that this level investment produces information that is usable for a variety of applications to meet the needs of communities, and society at large. Unfortunately, there are disconnects between these groups that, more often than not, result in the implementation of monitoring systems without sufficient consideration of the information needs of stakeholders as a group (Christian et al., 2006).

[1]https://cdn.ioos.noaa.gov/media/2018/02/US-IOOS-Enterprise-Strategic-Plan_v101_secure.pdf

In parallel, the ocean economy is beginning to be well understood. In 2010, ocean industries were estimated to have contributed US$ 1.5 trillion to the global economy (OECD, 2016). The OECD report states that by 2030, many ocean-based industries have the potential to outperform the growth rate of the global economy, both in terms of value-add and employment. The OECD analysis of a "business-as-usual" scenario, predicts that, between 2010 and 2030, the ocean economy could more than double its contribution to global value added, reaching over US$ 3 trillion. It is, therefore, clear that the ocean provides a wealth of economic and social benefits and that these benefits are underpinned by ocean observations, measurements, and forecasts. However, there have been no comprehensive global attempts to value these benefits, although numerous case studies have attempted to quantify components of the benefit accruing from the collection and use of such data. In aggregate, the cost of obtaining and using such data is almost certainly only a small percentage of the value of the benefits derived (Rayner et al., 2018).

Deriving economic benefit from the oceans must be considered in conjunction with the often-concomitant deterioration of ocean health. Plastics pollution and ocean acidification are now joining harmful atmospheric emissions, the spread of invasive species and overfishing as serious societal challenges that must be addressed. Impacts from changing climate including rising sea levels and coastal storms and flooding are also of serious concern. Many observation and monitoring programs inform policies designed to enable protection of the global oceans. These include global policies such as the United Nations (UN) 2030 Agenda, and in particular, Sustainable Development Goal 14 (SDG14) which covers ocean conservation and the sustainable use of ocean, sea and marine resources. Furthermore, ocean observations are important elements of global assessments such as the World Ocean Assessment (WOA) and those undertaken by the Intergovernmental Panel on Climate Change (IPCC).

In order to achieve SDG14, and the wider Sustainable Development Goals (SDGs) it is equally important to recognize societal processes alongside that of contributions from science and technology. The United Nations Framework Convention on Climate Change (UNFCC) and the 2018 Talanoa Dialogue Platform is an example of the greater recognition of the role of humanity in bringing about change. Talanoa, a traditional Fijian word meaning "to talk or speak" is used in the Pacific and has been adopted more widely to describe a process of inclusive, participatory and transparent dialogue, the purpose of which is to share stories, build empathy and to make wise decisions for the collective good. This philosophy should be adopted when considering future stakeholder engagement activities in ocean observation to maximize the contribution to sustainable development for the benefit of humanity.

This paper explores the importance of stakeholder engagement in ocean observation as demonstrated by a number of case studies. It begins by introducing stakeholder engagement within existing coordinating frameworks such as the United States's Interagency Ocean Observing System (IOOS®), and the European Ocean Observing System

(EOOS) and the grassroots approaches used; where IOOS was primarily established as a community-driven initiative and EOOS seeks to build on the same democratic model. The paper then highlights other initiatives such as public–private partnerships, which are typically established to fulfill a business or societal need, and, introduces the role of the "third" or voluntary sector. This sector typically comprises Non-Governmental Organizations (NGOs) with a broad remit to develop and share knowledge and promote community participation for public benefit. The paper will explore the value stakeholder engagement can bring as well as noting existing shortcomings, such as the lack of geographical range in the cases presented which are based on the knowledge and experience of those contributing. Finally, the paper will make recommendations for the future.

THE ROLE OF STAKEHOLDERS IN CREATING SOCIETAL VALUE FROM COASTAL AND OCEAN OBSERVATIONS

Basic Principles

In the ocean and coastal science community, there has long been an appreciation of the need to create an ocean observation network. However, the importance and urgency of growing the network and engaging a wider range of stakeholders has increased congruently with an increasing understanding and appreciation of ocean issues. A successful ocean observing network includes managers, policy-makers, civil society, general scientists and specialists (including scientists undertaking observations), marine service providers and geo-spatial technology stakeholders. In such a network, each stakeholder has a clear understanding of their unique role and responsibility as well as their related needs. The GEO Blue Planet Initiative is working to build and support such a network. It aims to support the production of relevant, useful and timely data to inform ocean and coastal decision-and policy-making. The Blue Planet initiative acknowledges three pillars for the success of such a network: convergence around common goals, effective communication and the co-production of information and knowledge.

Converging on Common Goals

The SDGs, the Sendai Framework and many others represent global objectives for human development. These internationally negotiated agreements provide clear development goals. These include the sustainable use of our oceans, and security for our coastal populations, among others. As such there is increasing convergence on these common goals which can act as catalysts to assemble human talent, to explore business and technology opportunity, and build collaborations (Hov et al., 2017).

The need for the ocean observation community to respond to global objectives and challenges is increasingly being acknowledged (Guo et al., 2015; Aitsi-Selmi et al., 2016; Anderson et al., 2017; Benedetti-Cecchi et al., 2018). If the coastal and ocean observing community can drive a specific agenda linked to these societal objectives, then the likelihood of a successful network and co-production of information and knowledge can be realized. Mutual recognition of priorities is a strong starting point for collaboration and the formation of partnerships.

Effective Communication

Ocean observing users require data products and information which respond to their needs. These users may be those for whom the data has been specifically collected, or those using data-derived information to inform decisions, e.g., on managing ocean and coastal resources while preventing or mitigating effects on the supporting ecosystems and species therein. These users need to have the information in a way that allows them to make decisions based on scientific evidence but which are presented within a specific social and policy context. In turn engagement of ocean observing users is essential in order to design fit-for-purpose ocean observing systems and networks. Communication is a critical means to enable both the collection of user requirements and the provision of information and products that respond to the user needs. However, targeting communications to such a variety of stakeholders requires a thorough stakeholder analysis and personalized approaches.

The recent inclusion of the importance of ocean observing in several high-level policy statements and agendas (Agenda 2030, the United Nation Ocean Decade for Sustainable Development, G7, etc.), gives an unprecedented gravitas to the ocean observing community in explaining the relevance of their work to policy and society. Scientific evidence is paramount in the development of policies to meet major global challenges. As a result, there is a need to better understand opportunities and constraints to science use to inform policy design and implementation, as there is a need to understand how to make science usable (Dilling and Lemos, 2011; Lemos et al., 2012; Kirchhoff et al., 2013). The usability of science has been widely debated by the climate change science community (van Aalst and Agrawala, 2005; Moss et al., 2013; Kirchhoff et al., 2015). Similarly, the usability of ocean observations is due serious consideration. Traditionally, the scientific community has assumed that if decision-makers are provided with reliable science information, this information will be used to make improved evidence-based decisions (Nisbet and Scheufele, 2009). This assumption is overly simplistic and inaccurate. There remains a compelling need for alternative approaches to the engagement between the producers of scientific information and the target users (practitioners) of this information (Kollmuss and Agyeman, 2002; Nisbet and Scheufele, 2009; Cone et al., 2013). Science–policy interfaces emerge as enablers of a sustained relationship between the ocean observation community and the users of observation data and information.

To adequately inform decision- or policy-making, scientific evidence-based recommendations should also consider the political, cultural and social debate that inevitably and justifiably surrounds these major issues (Horton and Brown, 2018). Ideally, scientific evidence expands alternatives, clarifies choice and enables policy-makers to achieve desired outcomes (McNie, 2007). Therefore, scientific evidence submitted as policy advice should be drawn from natural and physical sciences, and the humanities such as social science, law and economics. This multi-disciplinary approach to delivering scientific advice to policy is still new to the ocean observing community. Communication and capacity building are required within the community, to understand policy drivers and constraints and to learn how to communicate with policy makers in an impactful fashion. The same applies to building effective relationships and mutual trust between the scientific community and industrial users of the ocean information, space and resources. Furthermore, delivering information and services to the industrial end-users, often involves the engagement of intermediary service providers who transfer and customize the ocean observing data into tailored products for end-users.

In summary; effective engagement between sciences and users is inherently tied to effective communication (Vogel et al., 2007). There is increasing support for initiatives that support effective communication by building relationships, trust and dialogue (Nisbet and Scheufele, 2009). Effective communication is also becoming embedded in the core objectives of the global initiatives like GEO Blue Planet or within European associations like EuroGOOS. However, building and maintaining stakeholder interfaces and relationships is time consuming and resource-intensive. While communication has been broadly recognized as a priority, adequate funding for it remains a challenge in the ocean and coastal science community.

Co-production of Information and Knowledge

Once a common objective has been identified, and relationships and mutual understanding have been established, the next step is to co-produce usable information and knowledge. Information produced through collaboration between scientists and practitioners, funders, technology developers, politicians and other users have been shown to produce more usable and concrete outputs (Lemos and Morehouse, 2005; Walter et al., 2007; Roux et al., 2010; Lemos et al., 2012; Kirchhoff et al., 2013; Reed et al., 2014; Howarth and Monasterolo, 2017; Djenontin and Meadow, 2018). Djenontin and Meadow (2018) have recently outlined the elements, principles and processes involved in co-production of information and knowledge based on the growing body of research on this topic (**Figure 1**).

These variables are not meant to be exhaustive but can be used as a starting point for successful co-production of information and knowledge (Djenontin and Meadow, 2018). It is important that parties embrace the blurring of 'traditional' roles of scientists and practitioners (Vogel et al., 2007; Dilling and Lemos, 2011).

The Need for Innovation and Usable Information

There is a need for technological innovation, alongside innovation in designing and implementing policy, and social responses to achieving global sustainability. This is considered one of the grand challenges for Earth System Sciences (Reid et al., 2010). When considering science in service of society: private, public and academic institutions, together with NGOs, need to agree a strategy for translating and transmitting information in the most efficient and effective way (Hov et al., 2017).

Ocean observation is inherently technical and scientific in nature. Accordingly, there are constant technological advances and disruptions, and new industry "players," both public and private (Denis et al., 2017; Levy et al., 2018). Similarly, there is a large and dynamic network of observation technologies, and institutions and agencies that also benefit from, and drive, advances and disruptions. Examples of disruptive technological advances in the field of ocean observation and more widely include NOAA's Big Data Project[2]; EO Data Cubes and Analysis Ready Datasets (Giuliani et al., 2017; Nativi et al., 2017), crowd-sourcing and citizen science (Mazumdar et al., 2017; Brovelli et al., 2018; O'Sullivan et al., 2018) and deep learning and artificial intelligence (Lary et al., 2018). Related to this is the way that Big Data has changed the paradigm when it comes to the availability and exploitation of ocean observing data. Similarly, it challenges the interaction between data providers, service/application providers and users (of different types) (Ceccaroni et al., 2018). These disruptions are not limited to technology and technology partners, but include a change in how observational data are transformed to inform specific societal needs.

The mission and objectives of space and earth observation agencies and institutions are increasingly reflecting the need to improve the distance between observational data and its use by civil society or industry. For example, Space 4.0i, an initiative of the European Space Agency (ESA), combines the global situation of space developments (Space 4.0) with the 'i' standing for an ESA-specific interpretation of the tasks. This includes objectives to: (1) innovate – through more disruptive and risk-taking technologies; (2) inform – through the reinforcement of the link with large public and user communities; (3) inspire – through the launch of new initiatives and programs, involving both current and future generations; and (4) interact – through enhanced partnerships with European countries, European institutions, international players and industrial partners. Through this initiative ESA aims to be in a position to drive the realization of a 'united space in Europe' for the benefit of its citizens and economy. This approach has been taken a step further by the National Oceanic and Atmospheric Administration (NOAA)'s Big Data Project which has made available a wide range of data from satellites, radars, ships, weather models, and other sources in a cloud environment. This approach mitigates the need to download and store the terabytes of data generated on a daily basis, rather it analyses in the cloud which in turn benefits from high availability, scalability and resilience required by users. NOAA believes this approach will foster innovation and provide value to users.

It is appropriate to acknowledge that the current engagement between the broader EO community (predominantly, space observation) and users (using their broadest conceivable definition) is adding value (Denis et al., 2016; Hossain et al., 2016; Vasko et al., 2017). The commercial Earth Observation data market (in Europe) was estimated at $1.7 billion in 2015 while the

[2]https://www.noaa.gov/big-data-project

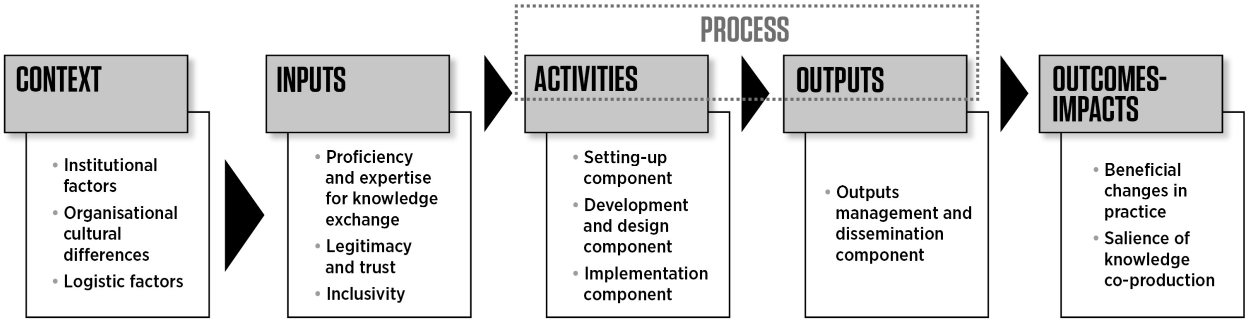

FIGURE 1 | Variables of knowledge co-production work. Source: Djenontin and Meadow (2018).

value-added service market was estimated to be worth $3.2 billion (Denis et al., 2016).

Embracing Diversity and Interconnectedness

Linking scientific information obtained from observations to users is challenging and complicated. The traditional value chain of data–information–knowledge has been conceived as a linear process. There is, however, a growing body of literature challenging this uni-directional value transfer (Crewe and Young, 2002; Jasanoff, 2003; Nowotny, 2003; Court and Young, 2006; Moll and Zander, 2006; Karl et al., 2007). Climate science and other disciplines of environmental science have embraced an alternative paradigm that views the relationship between science and practice as a complex web of connectivity and engagement across a wide range of stakeholders (Cash et al., 2006; Vogel et al., 2007). Within this web, there are multiple types of institutional arrangements and mechanisms for developing and disseminating scientific information (Dilling and Lemos, 2011). It is proposed that the ocean and coastal science community embrace the view of relationships as 'spider webs of interactions' that are 'composed of nodes and a multitude of ephemeral linkages,' as described by Vogel et al. (2007).

While the various types of institutions, programs, and groups within this web vary in the degree and mechanism of producing and transferring knowledge, all of these efforts seek to connect with users at different levels (Dilling and Lemos, 2011). It is important for the ocean observation community to recognize and value this web of stakeholders to achieve common global goals.

CASE STUDIES IN STAKEHOLDER ENGAGEMENT

Building a Regional Community-Driven Observing System – The European Ocean Observing System (EOOS)

The international Global Ocean Observing System (GOOS) program is a collection of observing systems, which provide near real-time measurements of the state of the oceans for observing, modeling and analyzing marine and ocean variables and which support operational oceanography worldwide. GOOS is a platform for international cooperation for sustained observations of the oceans, generation of oceanographic products and services and interaction between research, operational, and user communities. The implementation of GOOS activities occurs through programs such as GOOS Regional Alliances (GRA), JCOMM (Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology) and the IODE (Oceanographic Data and Information Exchange).

EuroGOOS is the principal GRA in Europe and considers the development of services to meet ocean health and climate user needs to ensure complementarity with the three GOOS thematic areas (real time services, ocean health and climate). EuroGOOS, together with the European Marine Board and many other partners, is strongly engaged in building the framework for ocean observing in Europe – The European Ocean Observing System (EOOS)[3].

EOOS is a coordinating framework designed to integrate Europe's ocean observing capacity. This framework supports a systematic and collaborative approach to collecting information on ocean state and variability in the long-term. Observation data, as a product of this effort, can then be used to inform sustainable development, and conservation of the marine environment. EOOS is building on existing initiatives and aims to be inclusive and community-driven, thereby meeting societal needs.

In the decade since OceanObs'09, European ocean observing has evolved considerably (EuroGOOS, 2016a,b, 2018[4]). However, Europe's capability in ocean observing and monitoring remains largely *ad hoc* (**Figure 2**). While there are some long-term monitoring programs in Europe, in many cases, funding is short-term and often only made at national, regional or even institutional level, especially for sustaining infrastructure and monitoring. A European alignment on funding and programming priorities is difficult due to the diversity of priorities in the ocean observing communities, from operational oceanography to wider research, and from environmental assessments to blue economy activities.

Key European science–policy events and foresight initiatives have called for the continent to develop a truly integrated

[3] www.eoos-ocean.eu

[4] http://eurogoos.eu/publications/

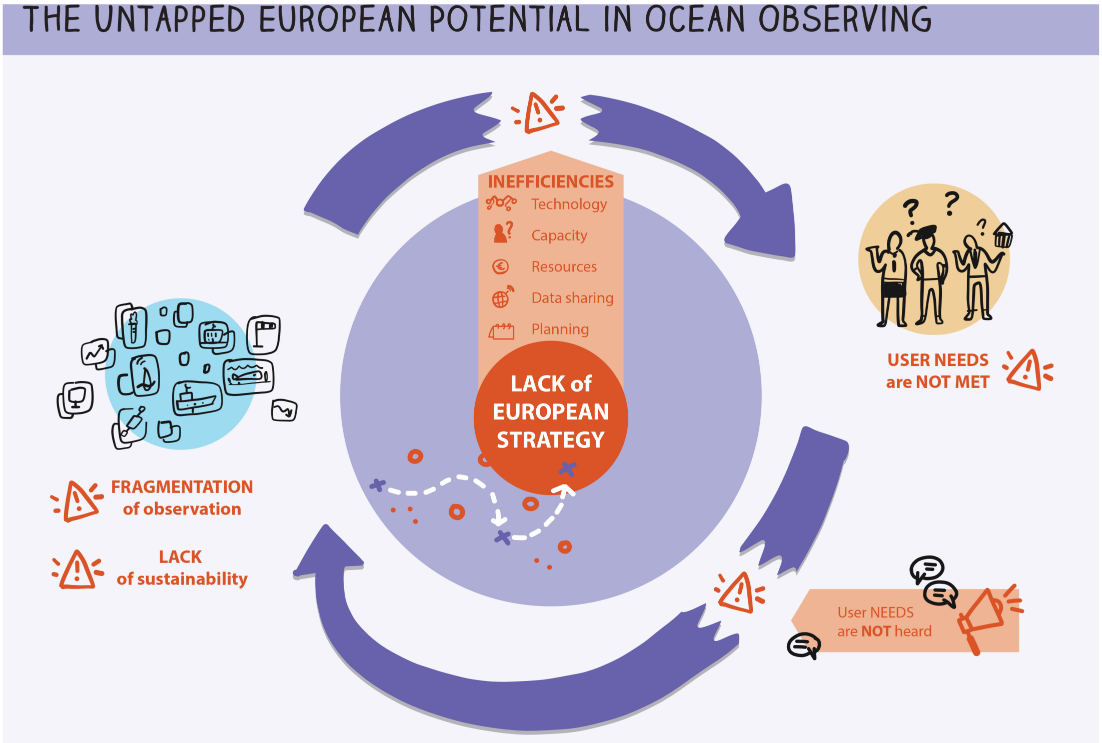

FIGURE 2 | The existing challenges and untapped potential of fragmented dispersed ocean observing efforts.

and sustainably funded system of European ocean observing systems. The purpose is to connect the full diversity of European ocean observation and monitoring infrastructures and stakeholders across the ocean observing value chain (EurOCEAN Declarations[5]; EurOCEAN, 2010, 2014; European Marine Board, 2013). EOOS is being developed as a framework to design and implement such integration. This is essential to address the current fragmentation across multiple sectors, regions, and countries, avoiding missed opportunities for collaboration and duplication of effort. Plans are not currently coordinated across different regions, ocean observing platforms and stakeholder communities (e.g., operational services and environmental monitoring). Furthermore, there is a gap in terms of technological and human capacities between the types of ocean variables observed. While observations for the physical variables have attained a high level of quality, data availability and aggregation, biological observations are lagging behind. This is due, to a large extent, to the considerable progress in automatization of physical measurements, as well as historical needs for physical oceanography services for navigation, meteorological services and maritime security. In turn, biological measurements are often collected primarily for scientific needs, rather than to provide practical industry solutions, and therefore rely on project funding. Fisheries management is an exception to this generalization where observations can be used to fulfill a very specific industry need. Traditionally ocean observations have not been well used by the fisheries industry where understanding of the mechanisms involved, the available data, or the large scale correlations are limited. In most cases, statistically significant correlations between population dynamics and population processes break down are yet to be established. This has led to advocating direct monitoring or developing management strategies that are robust to the variation rather than determining the relationships between population dynamics and oceanographic processes (Venkatesan and Sampath, 2017). In addition, biological observations are often complex and harder to automate, and the required human expertise is often lacking (e.g., taxonomy) (Benedetti-Cecchi et al., 2018).

The EOOS process requires openness and collaboration among the variety of ocean observing communities to help build a common strategic vision and a framework for Europe (EuroGOOS-European Marine Board, 2016). This has been driven in its initial stages through a collaboration between the European Global Ocean Observing System, EuroGOOS[6], and the European Marine Board[7], designed to stimulate the transition of EOOS from a concept into a tangible initiative.

By 2030, the EOOS framework will help make ocean observation a public utility in Europe. It will do this by strengthening coordination, strategy and sustainability in ocean observation. EOOS will be achieved with an operational

[5]http://www.euroceanconferences.eu/

[6]http://eurogoos.eu/

[7]www.marineboard.eu

implementation cycle that connects Europe's ocean observing communities, and offers regular opportunities for stakeholder input to evaluate, co-design and fund capability. Putting the needs of users at its center, EOOS will promote European leadership and innovation delivering crucial data to drive environmental policy, ocean governance, sustainable blue economy, and serve society (**Figure 3**) (European Marine Board-EuroGOOS, 2018). Strengthened and streamlined coordination of the European ocean observing capability will allow enhanced contribution to international frameworks and efforts, e.g., the UN Agenda 2030[8] and the United Nations Decade of Ocean Science for Sustainable Development (2021–2030)[9]. In addition to the broad requirements for ocean observing systems as previously described, drivers specific to Europe include the Marine Strategy Framework Directive[10], the Common Fisheries Policy[11], and the Maritime Spatial Planning Directive[12]. A more detailed list of known and emerging drivers requiring systematic ocean observing are listed in the EOOS Consultation document (EuroGOOS-European Marine Board, 2016)[13] and EOOS Strategy 2018–2022 (European Marine Board-EuroGOOS, 2018).

[8]https://sustainabledevelopment.un.org/

[9]https://en.unesco.org/ocean-decade

[10]http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

[11]https://ec.europa.eu/fisheries/cfp_en

[12]https://ec.europa.eu/maritimeaffairs/policy/maritime_spatial_planning_en

[13]http://www.eoos-ocean.eu/promotional-materials/

The EOOS framework is open and inclusive adding value to existing efforts across three focus areas:

(1) Better Coordinated and Sustained *in situ* Ocean Observing
EOOS will connect stakeholders across the ocean observing community with a focus on *in situ* observations, linked to remote sensing and modeling and to ensure full integration and responding to user needs.

(2) Ocean Variables Relevant to Society
EOOS will serve as a European focal point for systematic, long-term observation and monitoring as a forum to discuss, coordinate and implement international standards (e.g., Essential Ocean Variables and Essential Biodiversity Variables) and define European priorities for wider ocean variables. EOOS will promote innovative, adaptable ocean observing that can respond to evolving user needs, apply emerging technology and help invest in observations and Big Data initiatives.

(3) Integrated Ecosystem Approach
EOOS will promote multi-platform, integrated and thematic observing, which is crucial for sustainable management of ocean activities, and to assess ecosystem health and functioning and the interfaces with climate and the wider earth system.

Importantly, EOOS will build on strengthening existing capabilities, enhancing coordination at pan-European, regional and local scales, while bringing about an integrated European capacity for a global good. Regular stakeholder

FIGURE 3 | The added value of a coordinated EOOS framework.

consultations and events are organized to collect feedback on the EOOS development from a wide range of ocean observing implementers, funders and networks. Events taking place between 2015 and 2018 have informed the EOOS Strategy and Implementation Plan 2018–2022 (EuroGOOS-European Marine Board, 2018; European Marine Board-EuroGOOS, 2018).

EOOS will also connect ocean observing users, system implementers and funders across multiple geographical scales from national to regional and sea-basin scale. This requires buy-in and support from both the bottom-up community of infrastructure owners and data providers and top-down institutions (European Union and national competent authorities) that can provide political endorsement and, potentially, resources. The entire value chain should be considered from observations to information, products and services, including satellite and *in situ* observations, and data assimilation into models to produce products and services such as forecasts. In Europe, the Copernicus Program[14] (satellite) and Copernicus Marine Service[15] (ocean services) are key initiatives for the operational ocean observation value chain, whilst the European Marine Observation and Data Network (EMODnet) provides a central open access gateway to wider ocean observing and monitoring data and data products[16].

Early action for EOOS is to map existing infrastructures and stakeholders including the main ocean observing users (e.g., academia, public authorities, industries, policymakers). This mapping will be repeated and updated on a regular basis, most likely as a joint effort across key stakeholder organizations, and will inform EOOS stakeholder engagement.

EOOS promotes responsible research and innovation[17] by engaging stakeholders throughout the co-define strategy and planning process. This is done through a regular implementation feedback cycle. Users and data providers are routinely consulted to evaluate and update the user requirements. They contribute their knowledge of, and expertise in the latest scientific and technological advancements, as well as consider evolving policy drivers.

Stakeholder Interaction and Dialogue

EOOS implementation is progressively achieved through dialogue amongst the communities, users, and funders. Each milestone in the EOOS development is followed by a stakeholder engagement loop (**Table 1**).

EOOS will help funders (at national, regional, and European levels) to meet with implementers and users to exchange and develop a common understanding of the full European capability and the benefits of cooperation. This will allow funders to critically assess the real gaps in the system together with a business case for recommended upgrades to the system. The intention is that this will lead to economic efficiency, increased cost-benefit, and greater societal impact.

[14]http://www.copernicus.eu/

[15]http://marine.copernicus.eu/

[16]www.emodnet.eu

[17]https://www.marinaproject.eu/

TABLE 1 | Milestones in the EOOS development and stakeholder engagement.

Milestone	Stakeholder engagement
EOOS call for action at the European science and technology conference, EurOCEAN 2014**, October 2014, Rome**	
	EOOS expert brainstorming workshop (May 2015) defining the main EOOS scope and drivers
EOOS Steering Group is set up, early 2016	
	EOOS conference at the European Parliament, September 2016, Brussels
EOOS concept, drivers and goals refined in the consultation document, September 2016	
	EOOS stakeholder survey on the EOOS consultation document (December 2016–January 2017)
EOOS promotion for stakeholder buy-in through presentations at events and exhibitions	
	EOOS Forum (March 2018, Brussels) including brainstorming sessions across sectors and disciplines
EOOS draft strategy and implementation plan 2018–2022	
	Stakeholder consultation on the draft strategy and implementation plan (April–June 2018)
Finalization of the strategy and implementation plan	
	EOOS conference (November 2018, Brussels)

Strengthening and Diversifying Partnerships

By strengthening and expanding partnerships, EOOS will link closer with fisheries and environmental monitoring initiatives, as well as efforts outside of the operational Essential Ocean Variables (EOVs) and across Earth Observation sectors. EOOS will assist with regional and sub-regional alignment through existing initiatives such as the GRAs, e.g., EuroGOOS (and associated Regional Operational Oceanographic Systems), European Regional Sea Conventions, Regional Fisheries Management Organizations (RFMOs), etc. EOOS enhancements will also be advised to the GEO Blue Planet initiative to ensure complementarity in interactions with users.

The EOOS Implementation Plan 2018–2022 outlines six thematic areas: mapping and stakeholder engagement, policy context and foresight, implementation, funding, communications, and governance. For each thematic area, the plan proposes concrete activities. The plan also includes early actions where tasks have already been started by the community and action is ongoing or imminent.

In order to build a successful, long-term framework, the full cycle of EOOS implementation needs to be considered. **Figure 4** outlines key steps in the EOOS cycle, including

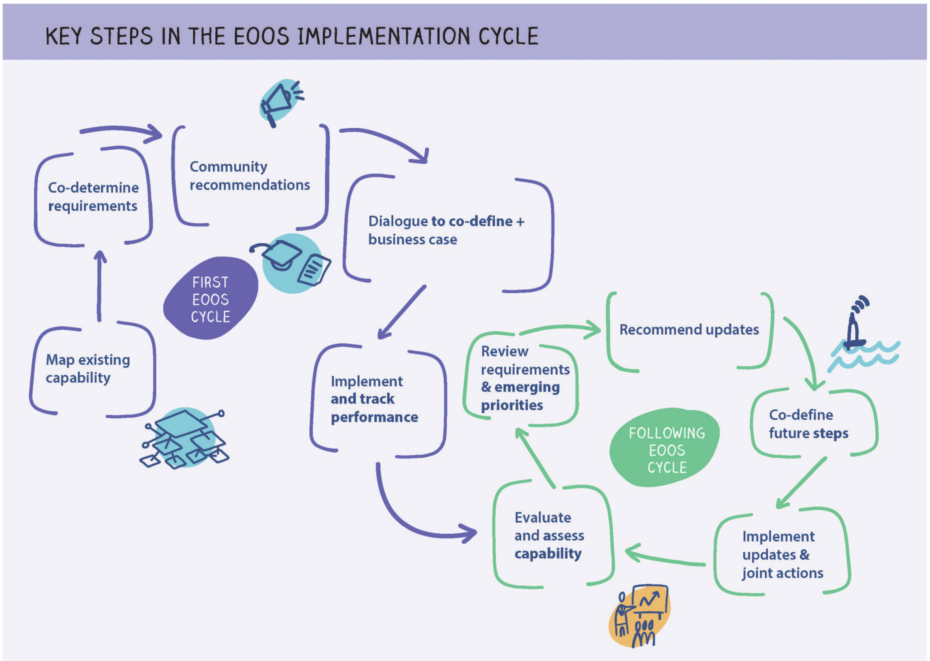

FIGURE 4 | Key steps in the EOOS implementation cycle showing the first cycle and then following cycles. Each cycle is proposed to last 5 years. Cross-cutting and intrinsic to each step in the EOOS cycle is stakeholder engagement, dialogue and co-design; communication and societal engagement; and governance and coordination.

the first cycle and how it could link to subsequent cycles. Stakeholder engagement, consultation and co-design are essential throughout the full cycle. For example, future ocean observing and monitoring requirements need to be co-defined through consultation with a broad range of users and wider stakeholders from academia to industry. And co-creation of observing system design would also need to bring in program managers and funders to ensure this is both fit-for-use and has a realistic business plan and financial sustainability. It is also noted that all stages would require stakeholders working across multiple sectors but also across geographical scales will be involved, spanning global to European and from Regional to National, including joint programming.

Communication Activities

EOOS outreach activities have been actively performed by EuroGOOS and the European Marine Board (EMB), including promotion at relevant conferences and events and the EOOS website. The EOOS communication strategy is being developed to encompass the discourse of several EOOS-related strategies (e.g., GOOS 2030 strategy and the UN Ocean Decade for Sustainable Development priorities), and set out a clear communications plan for the coming years.

The United States Interagency Ocean Observation Committee (IOOC) – Fulfilling National Requirements

In the United States, coordination among federal agencies, departments, and offices enables initiatives and activities that would not be possible by a single agency. By establishing relationships between regional, national, and global ocean observations, the United States Interagency Ocean Observing Committee (IOOC) enables powerful new approaches to scientific research and maritime operations. Ultimately, the human and organizational partnerships serve as the connective tissue between the diffuse system elements. Experts have long contemplated how best to design a governance structure that optimizes funding, technology transfer, and data integration. This effort culminated in the early 2000s with the release of the IOOS Implementation Plan. This plan formed 11 regional associations spanning the United States coasts, Great Lakes, and Caribbean (**Figure 5**) directed by the National Oceanic and Atmospheric Administration (NOAA). The IOOC, created by the executive branch of government and mandated by Congress, expands this network to strengthen partnerships across the federal government and provide strategic guidance. While NOAA provides the essential framework for core elements of the system, the IOOC represents the interests of the federal government and its vast cache of ocean infrastructure and programs – with the explicit objective for determining how to best utilize these resources for bolstering the IOOS enterprise.

Over the past decade, the IOOC has refined its model beyond immediate agency commitments and missions in order to develop consensus strategies and to lay the groundwork for future ocean priorities. IOOC members and staff connect programmatic initiatives to executive requirements, legislative directives, and community recommendations. The IOOC Co-Chairs and member agencies play a pivotal role in executing the

FIGURE 5 | The 11 regional associations spanning the United States coasts, Great Lakes, and Caribbean as established in the Integrated Ocean Observing System (IOOS®) implementation plan.

ocean observing initiatives and can leverage greater attention to their particular agency-based goals. The IOOC works closely with other Interagency Working Groups (IWGs) in other thematic areas including Ocean Partnerships, Facilities and Infrastructure, Ocean and Coastal Mapping, Ocean Acidification, and others. The IOOC is chartered by the White House Office of Science and Technology Policy (OSTP) Subcommittee on Ocean Science and Technology (SOST) and legislated by the Integrated Coastal and Ocean Observing System Act of 2009.

The IOOC is broadly focused on federal capacity-building by strengthening: interagency collaboration; community engagement; leadership opportunities; evaluation of effectiveness; and, program and organizational development.

The IOOC responds to the needs of ocean and coastal communities by harnessing the knowledge of multiple-agency representatives. This allows for increased understanding and visibility to address important scientific and technological challenges. One primary tool the IOOC uses for rapidly meeting both community needs and government mandates is through commissioning task teams of federal subject matter experts. IOOC task teams are comprised of three or more agencies and required to develop a budget and timeline for deliverables. This advance planning enables groups to successfully accomplish a set of objectives in a timely manner with staff and resources provided by the IOOC. For example, the previous suite of core ocean biological data variables was identified as outdated. An IOOC-commissioned task team addressed the issue by developing a federal survey, convening an expert workshop, and producing a series of reports published through White House Office of Science and Technology Policy. The result has been a greater focus on federal agency approaches to biological data collection and management in the oceans. It has also increased interaction regionally, nationally, and globally – along with positive reinforcement of the agencies participating on the team.

The capacity of the IOOC and its staff to support interagency projects is unprecedented among committees of this kind and permits more efficient workflows. IOOC Co-Chairs have a unique opportunity to guide these efforts working closely with IOOC members and stakeholders. IOOC members can lead task teams, developing greater visibility for their own agencies and helping to shape plans for improved ocean observations and data integration. This model for improving operational capability by connecting observing system agencies, institutions and other high-level authorities with user needs can be applied beyond the borders of the United States and provides a demonstration of how the approach of Vogel et al. (2017) can work in practice.

Project Azul: A Public–Private Partnership for Ocean Observation

Public investment in research and development in Brazil is not common and long-term commitment for funding research is often difficult. The discovery of vast reservoirs of pre-salt oil in ultra-deep Brazilian waters and the technological challenges associated with its exploitation have presented an opportunity for change. The availability of these resources has raised the interest of private companies in the regional dynamics of the oceans. This interest is also partly fueled by the National Petroleum Agency, which encourages oil companies to invest 1% of their exploration budget in research and development projects. Project Azul was established as a result of this scheme. This initiative is focused on the Santos Basin region, where the majority of pre-salt oil reservoirs in the South-eastern region of Brazil are located (**Figure 6**). The project started in 2012, fully financed by Shell Brazil, a private oil and gas operator.

The main objective of the project is the development of an ocean observing system for the Santos Basin region (dos Santos et al., 2015). The project is designed as a partnership between the Laboratory of Computational Methods in Engineering of the Federal University of Rio de Janeiro, and Prooceano, an ocean technology company headquartered in Rio de Janeiro. The university was responsible for numerical modeling and data assimilation while Prooceano was responsible for the observations and data analysis (Project Azul Dataset, 2018). During the pilot phase which took place from 2012 to 2016, 60 surface drifters, 36 Lagrangian floats, and 5 underwater gliders were deployed. These datasets were used to produce a consistent dynamic representation, and to increase the oceanographic knowledge of the Santos Basin region. Temperature and salinity profiles collected by gliders and floats (along with remote sensing data) were assimilated by a regional ocean model and evaluated against drift trajectories and others non-assimilated data sets (Fragoso et al., 2016). The assimilation of data resulted in significant improvements in the representation of important mesoscale features of the basin.

One of the important outcomes of Project Azul was the investment in professional and academic training in operational oceanography. During the pilot phase of the project, peer-reviewed articles, book chapters, doctoral theses, master's dissertations and undergraduate monographs were produced from data and information generated during the project. Other important outputs from the project are still under development but will permit a more accurate understanding of the ocean dynamics in the south-eastern Brazilian region. Professional and academic capability in operational ocean modeling and data assimilation was also developed through establishing cooperative relationships with international universities and other scientific institutions.

Project Azul also made a significant contribution to the wider acquisition of oceanographic data in Brazilian waters such as the hydrographic datasets collected with the use of gliders. The use of gliders and the other Lagrangian sensors permitted a continuous and systematic data acquisition that is of fundamental importance to achieving a consistent understanding of the time-variability

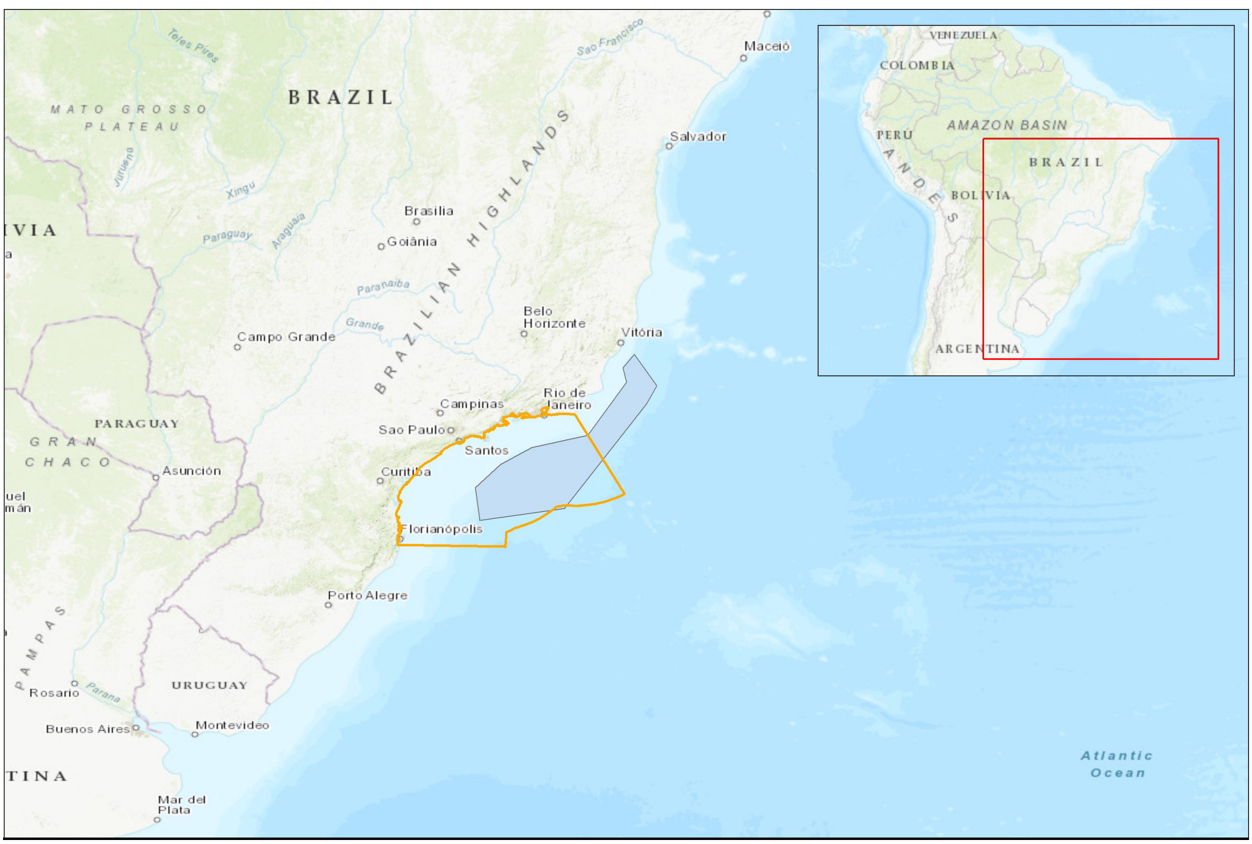

FIGURE 6 | Santos Basin region (red line) and the pre-salt reservoirs.

of local ocean dynamics (**Figure 7**). This kind of effort was unprecedented in Brazilian oceanography mainly because of the costs involved.

Another significant contribution of the project is that all the data acquired during the project is freely available to the scientific community. This has greatly advanced the state of knowledge on ocean dynamics and ocean sciences more broadly in Brazilian waters. All of the information generated is updated in near real-time on the project website. The website displays each sensor trajectory and the latest vertical profiles and geostrophic sections computed from the acquired data. Regional ocean model forecasts are also made available.

Project Azul II

The second phase of project Azul begun at the end of 2017 and will continue until 2021. The second phase of the project aims to expand the ocean data acquisition with the addition of an autonomous surface vehicle and two instrumented anchor lines. The new sensors will allow an even more comprehensive observation of the ocean dynamics and will include both meteorological and wave data. Other important developments include the implementation of an operational wave forecast model; an increase in the regional ocean model horizontal space resolution and improvements related to the data assimilation system. Furthermore, other important developments include optimizing the use of autonomous vehicles such as making changes to the predefined gliders routes in order to better inform the hydrodynamic ocean models.

Project Azul proves the feasibility of a public–private partnership for systematic long-term oceanic observation with tangible benefits to all parties involved. It is important to emphasize that Project Azul has improved the oceanographic knowledge of Santos Basin region and it is recommended that subsequent initiatives follow the proven partnership model of the project. There are benefits to applying the model, not only to the whole Brazilian ocean margin but also in other

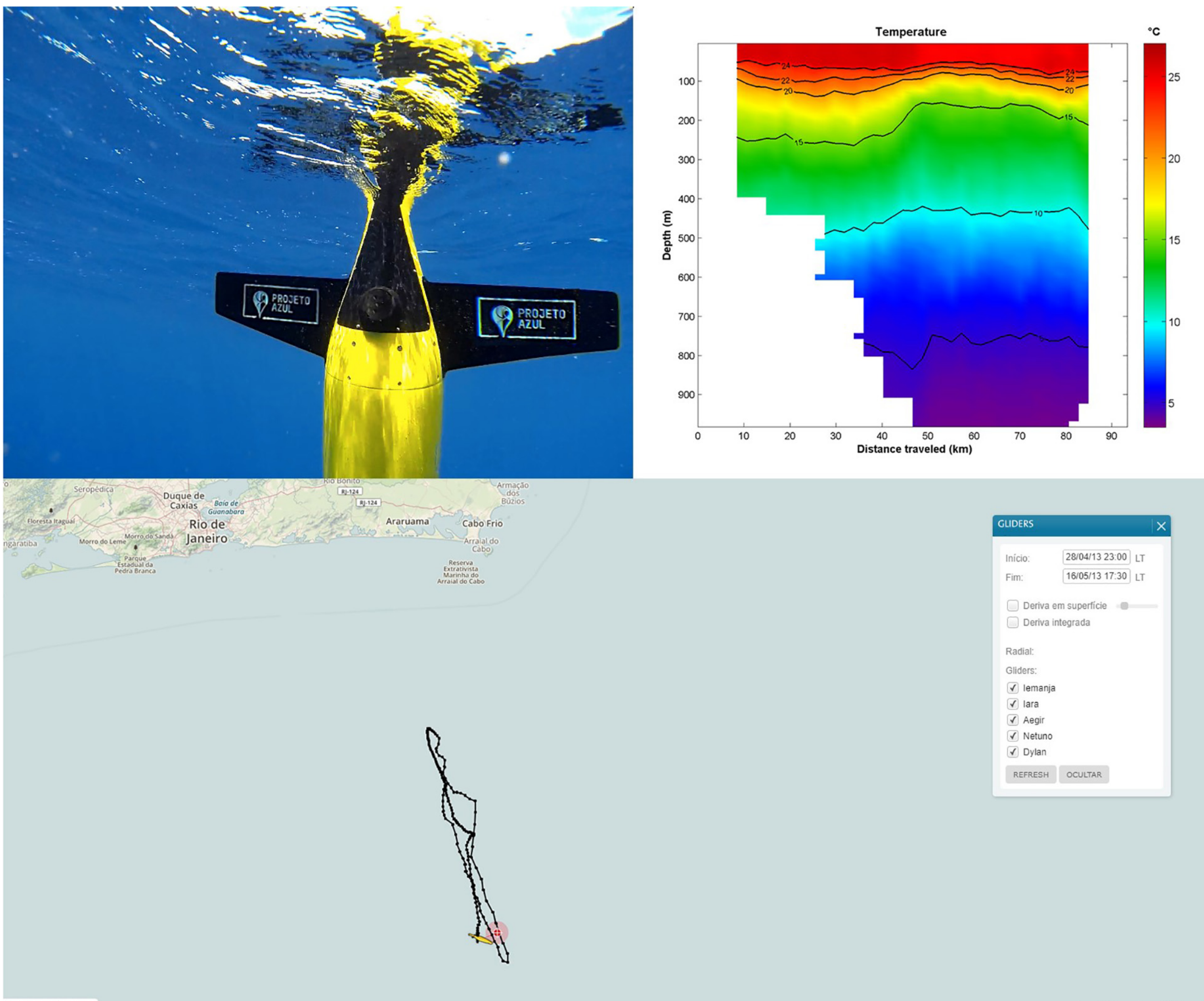

FIGURE 7 | The glider used in project AZUL, the position of a monitored section lower right side and a temperature vertical section generated by the acquired data.

developing countries where financial constraints may be limiting progress in ocean sciences. However, the principals of private–public partnerships can support advances in ocean observing independent of financial constraints and provide a case study of what can be achieved through the personalized stakeholder engagement and dialogue promoted earlier in this paper.

Partnerships Between Academic Institutions and the Private Sector – The Coastal Data Information Program (CDIP)

There is a need to establish how academic institutions and United States federally/government funded ocean observing and science programs can better foster private partnerships and to understand how these partnerships can fulfill a specific need for industry, to transition research to operations, and to ensure returns from the research investment. The Coastal Data Information Program (CDIP), of the Scripps Institution of Oceanography, University of California, San Diego, has identified some guidelines which have evolved over time to support this type of partnership.

Since the CDIP's inception in 1975, more than 275 wave observation stations have been deployed around the coastal United States, Caribbean and Pacific Islands (Thomas, 2018). The United States Army Corps of Engineers (USACE) and the State of California have been the primary funders of these stations. However, significant public–private partnerships have developed between the State of California, several federal agencies and with industry.

The Port of Long Beach

A key example of the CDIP's public–private partnership is that with the Port of Long Beach, California. The port at Long Beach handles US$ 180 billion in trade annually, with 175 shipping lines connecting to 217 national and international seaports. Presently, 50% of California's oil comes in through the port which has a containment capacity of 3 days. One of the challenges for the port is how to address the transiting of the larger vessels. Andeavor (previously Tesoro and now Marathon Petroleum) has been leading the "Under Keel Clearance" (UKC) project at Long Beach in order to address this issue. At present, the channel depth is 85 ft. Prior to the start of the UKC project, the deepest draft allowed in the port was 65 ft. This conforms to the port mandate of a 10% under keel clearance. To improve operational efficiency, Andeavor's goal was to establish the ability to transit the vessels safely into port with a 69-ft draft allowance. The tides and wave action play a significant role in these channel transits. For every degree that an 1,100 ft crude oil tanker pitches, 9.6 ft of draft is lost. For this reason, Andeavor and several other oil companies transfer cargo to smaller vessels in order to enter port facilities – a process known as lightering. Since the lightering process is costly and potentially hazardous for human safety and the environment, Andeavor paved the way for eliminating offshore lightering. However, in order to do so there is a reliance on the timely delivery of data for their operations, knowledge of the metrics for data uptime, and access to high quality and responsive personnel.

In collaboration with Jacobson Pilots, the Marine Exchange of Southern California, the California Oil Spill and Response, the National Oceanic and Atmospheric Association (NOAA), the USACE and CDIP, Andeavor embarked on the UKC project in 2014. They contracted a Dutch firm, Protide, to analyze and display, in real-time, the parameters required to transit these 1,100-ft tankers into the port. The parameters required to calculate the UKC are tides, high-resolution bathymetry, wave observations and wave forecast models. NOAA Center for Operational Oceanographic Products and Services (CO-OPS)[18] provides the tides, NOAA Coast Survey[19] provided the bathymetry, and NOAA National Centers for Environmental Prediction (NCEP)[20] provides the real-time wave forecast model, the Nearshore Wave Prediction System (NWPS), and WaveWatch III (WW III). CDIP is providing the wave buoy observations and a short-term wave forecast, which is a 1-h nowcast of the wave model.

Observations and Nowcast Model

Since the pitching of the vessel is caused by waves on the stern of the vessel, it is essential to have access to accurate wave data. Three CDIP buoys in the San Pedro Bight support this project. With central-infrastructure support from the USACE, the San Pedro Buoy has been supported from the California Department of Boating and Waterways since 1981. It is deployed in the separation zone of the westerly shipping lane. The San Pedro South Buoy, with support from Andeavor, has been deployed since 2014, and is located in the separation zone of the southbound shipping lane. The Long Beach Channel Buoy was deployed in 2015 with initial support from the NOAA Integrated Ocean Observing System (IOOS®) and additionally Andeavor. These three buoys serve as a real-time update and validation for the nowcast and forecast wave models (**Figure 8**).

As mentioned, both NOAA and CDIP are providing wave models for the UKC project. The NOAA WW III and NWPS model suite consists of global and regional nested grids. These wind-driven forecast models are invaluable for vessel scheduling of the port transits. CDIP provides a buoy-driven wave model that assimilates the suite of CDIP high-resolution, offshore buoy data from the Southern California Bight. CDIP is providing a one to 3-h swell forecast which is highly accurate since it is based on the buoy observations themselves. This short-term forecast is essential for making any last-minute correction to the transiting plans (**Figure 9**).

Harnessing User Engagement to Develop Guidelines

Following engagement and discussion with the user a set of guidelines was developed based on finding solutions to the problems and challenges faced by a specific user. In the case of the CDIP these were:

Offer a reliable, robust and high-quality instrument that is designed for a specific need: CDIP deploys the Datawell wave

[18]https://tidesandcurrents.noaa.gov/
[19]https://www.nauticalcharts.noaa.gov/
[20]http://www.ncep.noaa.gov/

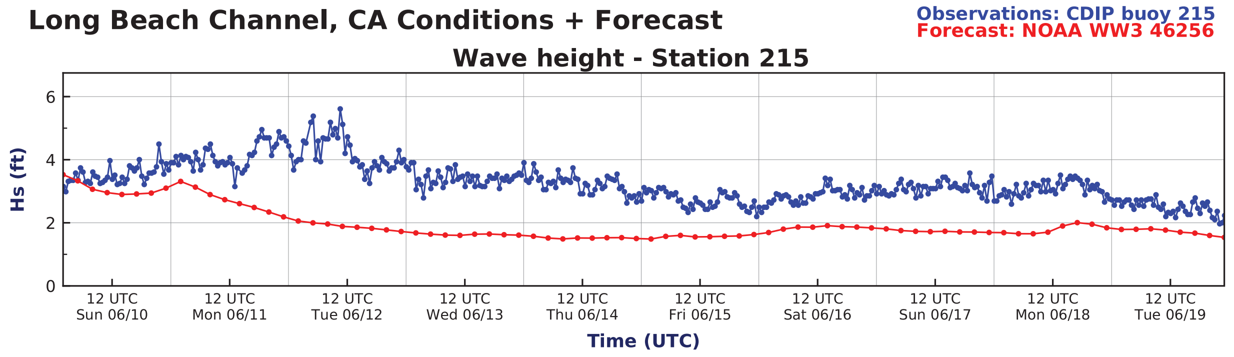

FIGURE 8 | The observations from the Long Beach Channel buoy are often higher than the WW III forecast model due to the reflection off the Long Beach breakwater and the local offshore bathymetry.

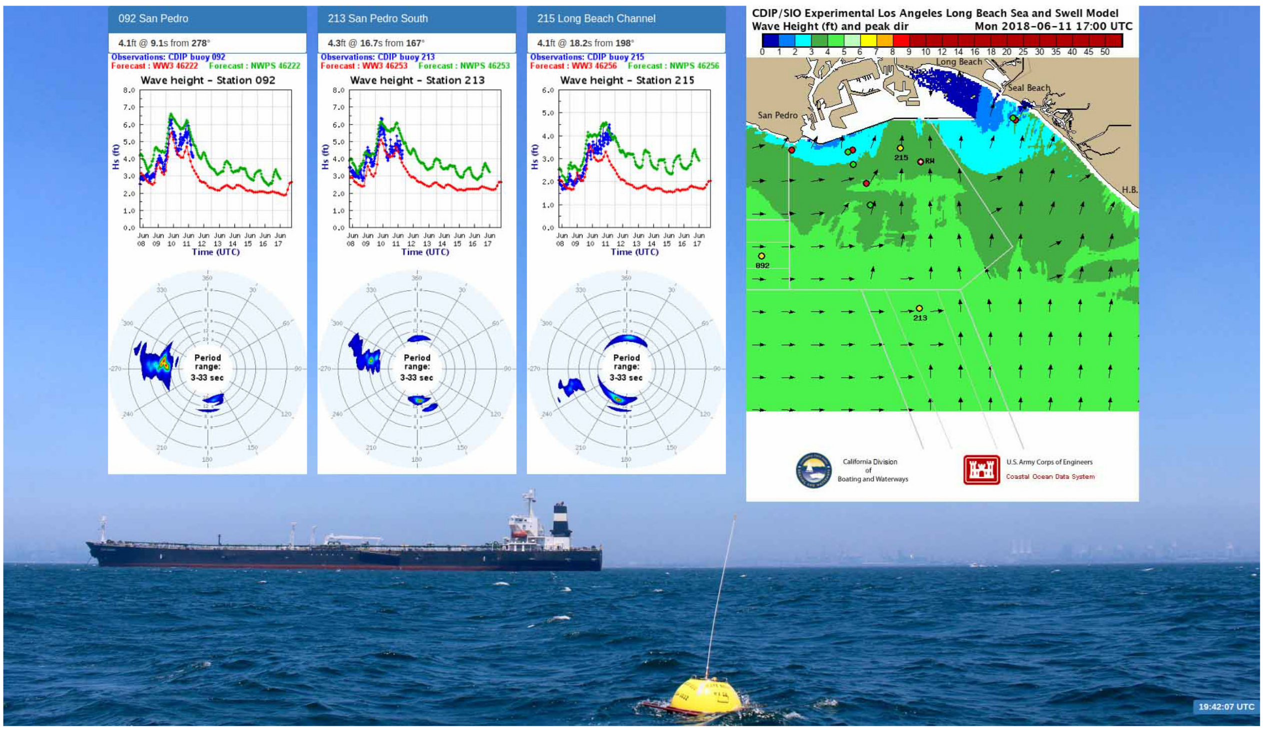

FIGURE 9 | A web display at the Marine Exchange of Southern California, San Pedro updates every 30 min (http://cdip.ucsd.edu/custom_pages/marine_exchange/). The three graphs highlight the differences between the buoy observations (blue), WW III (red) and the NWPS (green).

buoys whose wave motion sensor is based on a stabilized platform, accelerometers, and magnetic compass. These buoys have an accuracy of 0.5% of the measured value and a resolution of 1.4° for wave direction. The buoys are known for being robust and reliable. CDIP calculates the data return for each buoy-year. In 2017, the return for San Pedro was 99.95%, San Pedro South 97.49% and the Long Beach Channel Buoy 99.99%.

Provide data analysis which is based upon comprehensive, automated quality control routines that include human decision-making as appropriate: Rigorous quality controls are implemented at several stages in the processing. On-line documentation describes the quality control measures that are incorporated into CDIP's basic data handling programs, outlining the methodology for data checks and editing. The Quality Control of Real-Time Data (QARTOD) describes the appropriate quality control measures[21]. There are very specific quality control checks that are unique to the Datawell buoy, such as the check factor and the vertical and horizontal ratio of the orbital motion. This is a good indicator of the bio-fouling or damage to the accelerometer (see footnote 20) (**Figure 10**).

[21]https://ioos.noaa.gov/project/qartod/

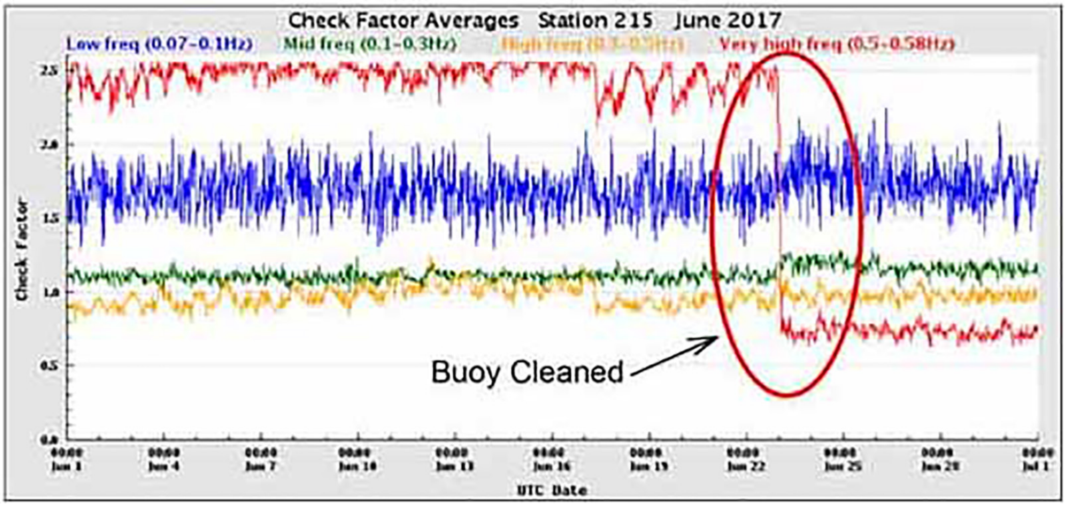

FIGURE 10 | The check factor indicated biofouling on the Long Beach Channel Buoy. As a result, divers cleaned the buoy and mooring line, returning the check factor to a normal signal.

Provide reliable dissemination of the complete data set (time series, spectral, parameter), both real-time and historic: CDIP receives the complete xyz surface displacements at 1.28 Hz and spectral files from the buoy every 30 min. After the quality control process, the data are disseminated and archived at CDIP in Network Common Data Form (NetCDF) format, complete with International Standards Organization (ISO) and climate forecast (cf)-compliant metadata. All of the data and statistical products are available on the CDIP website. These data are also disseminated to the National Data Buoy Center for transmission on the Global Telecommunication Service and National Weather Service marine broadcasts. For the Port of Long Beach project, CDIP serves the latest NetCDF files via the Thematic Real-time Environmental Distributed Data Services (THREDDS) to Charta/Protide in Rotterdam where they are ingested into the UKC analysis.

Automate a suite of diagnostic information in order to minimize downtime: CDIP has a suite of diagnostic applications in place. These applications monitor the complete end-to-end system, including system hardware, data transmission via iridium, analysis, data dissemination and offsite positioning.[22]

Provide access to a human response to user requests in a timely manner: If these data are used for critical operations such as shipping and port navigation, or health and safety concerns, personnel should be available 24/7. The IT and Management of CDIP are on "pager duty," which consists of a 1-month rotation of 24/7 monitoring. If there is an issue with the buoy, i.e., it has not updated in over 2 h or if the buoy is offsite, the team will be emailed and a message sent to the person on duty. Depending on the issue, the appropriate personnel will be notified to correct the problem.

[22]http://cdip.ucsd.edu/diag

These guidelines demonstrate a potential path for transitioning research to operations based on a specific user case.

OTHER CONSIDERATIONS IN STAKEHOLDER ENGAGEMENT

Using Community Groups and Non-governmental Organizations to Support Broader Stakeholder Engagement

Non-governmental organizations (NGOs) are widely recognized as key players within areas including economic development, human rights, humanitarian action and environment protection. NGOs are best-known for two different, but often interrelated, types of activity – the delivery of services to people in need, and the organization of policy advocacy, and public campaigns. The World Bank (Malena, 1995) defines NGOs as "private organizations that pursue activities to relieve suffering, promote the interests of the poor, protect the environment, provide basic social services or undertake community development" and states that NGOs contribute by introducing innovative approaches and promoting community participation. The World Bank also state that NGOs can facilitate greater awareness of diverse stakeholder views something which should be embraced by the ocean observing community.

Learned societies and professional bodies undertake community development for a specific sector of the community by affording professionals in the field they represent opportunities for career development and recognition of competency but in general do not fit the typical description of an NGO. They are membership organizations who bring together like-minded individuals. Most learned societies are non-profit organizations who strive to create, curate and disseminate knowledge and information- their activities typically include holding regular conferences for the presentation and discussion of new research results and publishing or sponsoring academic journals in their discipline. Examples within the ocean observing field include the Society for Underwater Technology (SUT), the Marine Technology Society (MTS) and The Oceanography Society (TOS) amongst others. Some also act as professional bodies, for example the Institute of Marine Engineering, Science and Technology (IMarEST), setting standards of professional competence and ethics and awarding appropriate qualified individuals certificates of registration. The role of a professional body, therefore is to ensure that employers, government and wider society can have confidence in the knowledge, experience and commitment of professionally registered individuals. This may be crucial when dealing with a diverse range of stakeholders where mutual trust has been identified as being a key component of successful engagement. Professional Bodies in particular strive to achieve technical excellence through members' expertise and provide impartial and independent to advice to, for example, policy-makers. Professional bodies constantly monitor policy relevant to their profession, seeking to anticipate unintended outcomes not appreciated during the policy formation and constantly ready to offer advice or make representations to help avoid poor decisions (Chartered Institute of Building [CIOB], 2016).

Like civil society groups and trade associations, learned societies and professional bodies have large networks – either through their own membership bases or by linkages with others with similar missions and visions. They can use their networks to advocate for and promote ocean observing but can play a much wider role as a whole – by running events on topical research issues, providing networking and career development support, training students, work with schools and universities to encourage young people to study and take up careers in oceanography, liaising with industry, and engaging with the media and the general public. One such example is the Oceans of Knowledge conference series organized by the Operational Oceanography Special Interest Group (OOSIG) of the IMarEST. The most recent event was held in collaboration with the industry liaison group of the Partnership for Observation of the Global Oceans (POGO) and discussed how ocean observations improve ocean, weather and climate prediction enabling better informed business decisions at sea, on land and in the air. Stakeholders have discussed the role that ocean observations and derived information play in supporting a wide range of industries. These stakeholders have included the shipping industry (route planning and search and rescue), oil spill response and offshore energy through to non-marine sectors such as insurance and re-insurance, retail and logistics and aviation.

There are a number of examples which can be used to demonstrate the potential that NGOs could have in engaging communities to make contributions to ocean observing should the right policies, incentives and education and engagement mechanisms be put in place. NGOs such as those which represent communities of individuals such as recreational fishers, surfers and sailors or who represent trades such as shipping, offshore oil and gas and renewables, aquaculture and fisheries have the potential to bring together groups to significantly enhance ocean observing.

Brewin et al. (2016) investigated the possibility of using recreational surfers (citizen science) as platforms for monitoring environmental indicators in the coastal zone to enhance sampling coverage required for better coastal management. The study involved a recreational surfer using a GPS device and a temperature sensor for a period of 1 year and then comparing the SST data collected by the surfer with data collected from a nearby oceanographic station (L4) and satellite observations in order to assess the accuracy. The conclusion was that high-quality data on SST in the coastal environment could be obtained using surfers. Additionally, the individual was provided details on their surfing performance using the data acquired from the GPS data. This may help motivate data collection by surfers. The study further concluded that 40 million independent measurements on environmental indicators per year around the United Kingdom coastline could be made by the surfing community. Surfer magazine[23] reports that a host of surf-related non-profit organizations have emerged that are taking the initial strides to enact positive social, environmental, and global change. Additionally, surfers are playing an important role in environmental governance through programs such as the World Surfing Reserves (Salamone, 2017). As such the potential for surfing NGOs to contribute to ocean initiatives is significant.

Ships of opportunity provide another means to improve coverage of ocean observations. Bucklin et al. (2001) and Melvin et al. (2016) highlighted the potential for the use of fishing vessels to undertake biological and environmental sampling. Commercial ships have a presence on the high seas second to none and offer society a feasible and cost-effective opportunity to contribute to solving observational deficiencies (SCOR, 2011). The Ship of Opportunity Program (SOOP) is an effort by the international community to address both scientific and operational goals for building a sustained ocean observing system. A number of partnerships such as OceanScope and more recently the World Ocean Council's Smart Ocean: Smart Industries have proposed formal partnerships with the maritime industries (commercial vessel owners and operators as well as others) to "enable systematic and sustained observation of the structure and dynamics of the ocean water column so that physical, chemical, and biological processes can be studied simultaneously across all the inter-connected ocean basins" (World Ocean Council, 2018)[24].

The Barcelona World Ocean Race[25] is another example of how working in partnership can support ocean observations. The Fundació Navegació Oceànica Barcelona (Barcelona Foundation for Ocean Sailing – FNOB) committed itself to working with the IOC of UNESCO in collaboration with other scientific research institutions, to protect the environment, in particular the ocean. To achieve this, the event provided a significant and valuable platform to contribute in assisting scientific research in the

[23]https://www.surfer.com/features/10-nonprofits-worth-your-love/
[24]https://www.oceancouncil.org/global-issues-platforms/program-focus/smart-oceans-smart-industries/
[25]https://www.barcelonaworldrace.org

world's oceans. Amongst other scientific projects each of the teams in the Barcelona World Race in 2015 deployed an Argo float to facilitate the study of the structure and dynamics of the water masses of the oceans.

Other Stakeholder Groups – A Case Study in Aviation

The case studies so far have largely focused on stakeholders that have a common interest – that they are direct beneficiaries of ocean observing products and services or are the providers of those products and services. Typically these stakeholders are easy to identify. However, there are other beneficiaries that may not recognize that they are stakeholders or who have not been identified as such. In the ocean observing community this might be non-marine sectors such as aviation or retail who benefit from weather forecasts that are improved by knowledge of the ocean state.

Ocean forecasts have been used for many years for operational planning in the maritime industries such as shipping, offshore oil and gas and offshore renewable energy generation. Decisions made during the phases of design, installation and operations are supported by ocean information from models (often incorporating marine observations through assimilation) as well as ocean observations themselves, often alongside weather products.

The importance of the ocean in the weather and climate system is increasingly being recognized and operational systems are now moving toward coupled prediction lead to improvements on seasonal to climate timescales but also to short-range forecasts. These improvements are being driven by the needs of stakeholders outside of the marine industries. Engagement of non-marine industries in understanding the benefits of supporting improved ocean observation and forecasting is particularly challenging but is essentially in ensuring the development of products and services are fit-for-purpose for beneficiaries.

One of the biggest users of meteorological services at the United Kingdom based Met Office is the aviation industry. As one of two World Area Forecast Centres for aviation, the Met Office provides global forecasts of winds and hazards for en-route civil aviation. The Met Office also provides forecasts for civil aviation for the United Kingdom, including forecasting for airports, leisure pilots (such as hot air balloonists), and United Kingdom helicopter operations. All of these services will be improved to an extent by the use of coupled prediction systems.

One specific case is that of the presence of fog at airports can which lead to delays and cancellations and in turn economic penalties and reputational damage to airlines (Roquelaure and Bergot, 2009). Fog has been shown to be particularly sensitive to air–sea interactions (Fallmann et al., 2019) and as such forecasts of fog can only be improved by ocean observations and derived models. San Francisco International Airport (SFO) provides a real case of where an improved knowledge of fog and low cloud would be advantageous. The airport has two closely spaced parallel runways. Both runways can only be used at the same time when the approach is completely clear of any cloud. Maximum flow rates change from 35 aircraft landing per hour when there is cloud, to up to 54 per hour once the clear conditions are reached. Therefore an accurate forecast of cloud clearance can be of considerable benefit for planning for both Air Traffic Control and the airlines coming into SFO. Low cloud over the ocean off the San Francisco coast comes in over the airport on an almost daily basis through the summer months. Forecasting the exact clearance time of this cloud over the runway and approach zone poses a challenge as conditions can vary considerably day-by-day and most weather models struggle to capture some of the finer detail in this area. The Met Office have recently taken part in an experiment running a high resolution (333 m) model over the San Francisco area with some encouraging results in terms of improved forecasts of cloud clearance. It is believed that running a high resolution coupled model over the shallow water of the bay would improve forecasts further due to representing the diurnal cycle of sea surface temperature (SST).

A further consideration is that of helicopter operations. Improvements in short term forecasts for convective events and lightning strikes, are valuable for identifying potential hazards to helicopter operations. On January 19th 1995, a lightning strike caused the ditching of an AS332 Super Puma helicopter into the North Sea, fortunately with no loss of life. Surface observations and radio-soundings indicated that convective cells with anvils circulated northward in a well-organized flow with some showers occurring on that day. These weather conditions are not unusual in the winter in the North Sea, with convective events typically associated with cold-air outbreaks. These conditions have resulted in a number of helicopters being struck by lightning (Broc et al., 2005). As well as the risk to life, lightning strikes to helicopters are expensive due to direct repair costs and subsequent loss of business while the helicopter is taken out of service. Improved forecasts of winter lightning risk and convection in the North Sea will improve the safety and efficiency of operations.

There are also benefits over to the aviation sector over longer timescales. For example, coupled models have been shown to improve medium-range forecasts of storm tracks, which in turn leads to improved forecasts of strong winds. Strong winds at airports can limit airport capacity, which is especially significant at busy airports such as London Heathrow which operates at 98% capacity. Consequently any disruption to capacity at Heathrow has a significant impact in terms of delays and short-notice cancellations of flights. Improved forecasts of strong winds at longer lead times enable improved planning and consequently airports can reduce disruption to passengers (for example, by proactively canceling flights in advance and rebooking passengers onto alternative flights). Finally, improved ocean forecasting has significant impacts on the quality of longer-range forecasts (monthly to seasonal) which enable the industry to better plan for events such as colder or warmer than average winters.

Other Stakeholder Groups – Indigenous Communities and Vulnerable People

A number of examples are available which demonstrate the benefit ocean observations can bring to support indigenous communities and which highlight the importance of conversations with those communities to establish what is required and the best method of delivery. The GEO Blue Planet initiative[26] describes the case of the European Union-funded MESA project (Monitoring for Environment and Security in Africa) which provides services to support the fisheries sector in West Africa. This consists of daily forecasts of ocean conditions sent via SMS to small-scale fishermen, as well as maps of potential fishing zones (PFZ) and daily bulletins on fishing vessel activities sent to fisheries managers. The service enables fishermen to increase their efficiency, reduce their costs and avoid venturing out to sea when the conditions are too dangerous.

The importance of the engagement of Indigenous people was recognized more than 10 years ago by the Sustained Arctic Observing Networks (SAON) Initiating Group. Here, Indigenous people raised the need to define their role in Arctic observing, including the role of traditional and local knowledge, the differences and similarities between knowledge systems, and restrictions on personal data and community based monitoring (SAON Initiating Group, 2008). In 2018, a statement made at the Arctic Observing Summit[27] further recognized that Arctic Indigenous Peoples have acquired a dynamic knowledge system, allowing for a broader understanding across biological, physical, social, and spiritual domains. It went on to say that to fully benefit decision making at all scales, this knowledge and Indigenous societal priorities need to play a central role in the development of future Arctic Observing Systems.

There are further considerations to be considered with vulnerable communities. When it comes to natural disasters such as hurricanes or floods it is often assumed that everyone is exposed to the same risk and as such it might be assumed that the impact to men or women is equal. However, statistics demonstrate that women and children are 14 times more likely to die than men during a disaster (Araujo et al., 2007). This vulnerability is further enhanced in societies where there are larger social inequalities where the socioeconomic positions of women can make them more vulnerable to disasters. This was evident in the 2004 Asian Tsunami where three times as many women as men died (Oxfam, 2005). The reasons varied but according to the report from Oxfam (2005) among the common factors included: that many men were out fishing or away from home, so had more opportunity to flee the tsunami while in India women traditionally wait on the beaches to unload the fish from the boats so were in an extremely vulnerable location. In general, men could run faster to escape the water and those caught in the sea used their greater strength to survive by clinging on to debris while in Sri Lanka the evidence was that women were simply not able to swim. In Aceh, the Indonesian province that bore the brunt of the disaster, many men had simply moved away to find work. Women, in contrast, were at home, and efforts to save their children slowed their flight.

However, the report from Oxfam (2005) suggests that rather than perceiving women as 'vulnerable victims' their specific perspectives and capacities should be used to develop the best way to responding to disasters and preventing such disasters in the future and this can be equally applied to their engagement with the development of ocean observing systems. By engaging women and representatives of vulnerable communities in the planning stages of ocean observing systems their knowledge and social practices could be used to better focus the observations and advise on the best dissemination of the information acquired to ensure the information required is delivered on time and in a format that can be easily understood and disseminated. As Aguilar (2008) state "Women's high level of risk awareness, social networking practices, extensive knowledge of their communities, task in managing natural environmental resources and caring abilities makes of them important players of effective risk assessment, early warning, disaster response and recovery actions." The Hyogo Framework for Action (HFA) in 2005 and its successor the Sendai Framework makes suggestions for how women should be included in preparing for natural disasters and these. The UNESCO program on disaster preparedness and prevention emphasizes the needs and roles of women in building a culture of disaster resilience which can also be applied to ocean observing. The World Meteorological Organization (WMO) has begun to take steps to address gender issues across weather and climate services that could and should be replicated by the ocean observing community[28].

Gender Diversity in the Ocean Observing Community

While section "Other Stakeholder Groups – Indigenous Communities and Vulnerable People" primarily relates to communities in the developing world and gender inequality when it comes to natural disasters there is an additional problem that exists across the globe. This is that there is a lack of diversity in those recruited and retained in roles across science, technology, engineering and mathematics (STEM) and this includes ocean observing. Firstly, diversity is crucial to develop the intellectual capital. For example, when any staff, researchers of faculty members leave an organization the knowledge base is eroded but this is prevalent in women leaving a company to have children, often returning to a lesser role. Secondly, a diverse mix of people lends itself to increased creativity and innovation- different ideas and different thinking. Thirdly, analogous to a company maintaining a competitive edge by having a better understanding of all potential customers and markets and their requirements this can be applied to users of ocean observation. For example, women have a unique approach to the application of science and its value in improving the quality of life. Finally, there are wider benefits where mixing diversity can lead to new priorities, perspectives

[26]https://geoblueplanet.org/blue-planet-activities/stakeholder-engagement-wg/

[27]http://www.arcticobservingsummit.org/sites/arcticobservingsummit.org/files/AOS_Statement_Aug24_clean.pdf

[28]https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/GAP_Draft.pdf?VDGolo0GoiMq9aT5FAHzO2uHJdKJTqmZ

and questions and ultimate effect the future direction of ocean observing.

DISCUSSION AND RECOMMENDATIONS

A Focus on Services

There is a growing industry that is converging on the concept of climate services (Brooks, 2013; Brasseur and Gallardo, 2016; Le Cozannet et al., 2017; Hewitt and Golding, 2018). Climate services focus on process, partners, users and stakeholders by pushing the transformation of science to benefit society. The concept is well-accepted to the point of the creation of a global framework and platforms (Global Framework for Climate Services[29], Climate Services Partnership[30]); symposia series (International Conference on Climate Services[31]), climate service research institutions (German Climate Service Centre[32]; Ouranos[33]), numerous climate service funding instruments (ERA4CS[34]) and a journal (Climate Services, Elsevier[35]).

It is reasonable to argue that by successfully defining a “climate services” concept, the science and scientific infrastructure supporting the conversion of climate science to policy enjoys a high-level of prominence. There is in fact many publications and literature describing the development of climate services to support public and private sector users and stakeholders (Guido et al., 2016; van den Hurk et al., 2016; Vogel et al., 2017). The coastal and ocean observing community has all the component elements to create a concept for a “services-focused science community” in the same way that climate services are now promoted. The intentional definition of an ocean observation services industry may be a powerful mechanism to enable the engagement between ocean observations and society. Networks and boundary agents such as GEO[36] and the GEO Blue Planet initiative[37] and GOOS can play a leadership role in this regard.

A New Science-Society Norm for Coastal and Ocean Observations

The science and technology basis for coastal and marine observations is dynamic and fast moving. Equally so, the society and how it responds to external stimuli is constantly changing. Within this context, there are basic principles to guide the creation of societal value from ocean observation products to ensure they remain relevant and useful to coastal and ocean communities and industries. Ocean and coastal information producers and practitioners should replace the view of a linear unidirectional value chain with that of a complex web of interactions and the role of transdisciplinary networks (Max-Neef, 2005; Binder et al., 2015; Polk, 2015). Sustainable development needs and the ocean observing fitness for purpose should be placed at the core. New technologies should be embraced and promoted within a new paradigm on open, user-friendly data access can enable society to engage as users and stakeholders within knowledge networks (Overpeck et al., 2011; Smith and Doldirina, 2016). The EOOS framework which is already stimulating partnerships in scientific and technological ocean observation foresight (e.g., Benedetti-Cecchi et al., 2018) demonstrates this value and shows that cross-disciplinary stakeholder dialogue and partnerships are crucial to take stock of current and emerging developments to ensure the current and future observing system is fit-for-purpose. The perception, trust and acceptance of science by society is not static and new technologies and governance mechanisms will require an equally novel approach to continue mutual engagement.

Converging on Common Objectives

As previously discussed the science community and society needs to converge around challenges or common objectives (Curley, 2016) and this is no different for the ocean observing community. Currently, there are particularly strong and globally acceptable expressions of common objectives for humanity. The SDGs, the Paris Agreement and many others provide the basis for the co-design and co-development of solutions for sustainability. It is important to recognize that science and the evaluation of scientific evidence cannot be divorced from the political, cultural and social debate that inevitably and justifiably surrounds these major issues (Cutcher-Gershenfeld et al., 2017; Horton and Brown, 2018). It is vital to recognize the importance of effective communication and invest in engagement and communication activities to develop capacity of all those within the network (Hossain et al., 2016).

Communicating Effectively

Effective communication is the cornerstone of building trust, partnerships and cross-disciplinary engagement needed to address the SDGs. Deepening stakeholder engagement and building advocacy and visibility is crucial for stakeholder and wider societal and policy buy-in, engagement and investment in ocean sustainability and responsible blue economy.

The relevance of ocean observation to society can be promoted through ocean literacy activities. An ocean-literate person understands the importance of the ocean to humankind; can communicate about the ocean in a meaningful way; and is able to make informed and responsible decisions regarding the ocean and its resources (Tuddenham et al., 2013[38]). Ocean literacy is also an imperative in establishing science–policy and public–private interfaces. Ocean literacy enables sharing understanding of basic concepts and facts about the ocean, but also developing common values and building personal emotional links to the ocean, which are paramount for

[29]http://www.wmo.int/gfcs/
[30]http://www.climate-services.org/
[31]http://www.climate-services.org/iccs/
[32]http://www.gerics.de/
[33]https://www.ouranos.ca/en/
[34]http://www.jpi-climate.eu/ERA4CS/
[35]https://www.journals.elsevier.com/climate-services
[36]http://www.earthobservations.org/index2.php
[37]https://geoblueplanet.org/
[38]http://oceanliteracy.wp2.coexploration.org/

responsible research and innovation (RRI) as well as policy and decision-making.

Citizen science is a growing area where society can be engaged in scientific data collection and, in many cases data analysis, while at the same time becoming more ocean literate (Garcia-Soto et al., 2017; Monestiez et al., 2017; Haklay et al., 2018; Visbeck, 2018).

Effective communication in ocean observing involves a broad variety of stakeholders at various scales, across disciplines and spanning many governance levels. Targeting communications to such a variety of stakeholders requires a thorough stakeholder analysis and personalized approaches. Furthermore, the recent inclusion of the importance of ocean observing in several high-level policy statements and agendas (Agenda 2030, the UN Ocean Decade for Sustainable Development, G7, etc.), gives an unprecedented gravitas to the ocean observing community in explaining the relevance of their work to policy and society.

Communication should be embedded in the core objectives of the many ocean observing initiatives and recognized as a priority and funded accordingly.

Making Better Use of the Case Study Approach

The value of the case study approach is well-recognized in the fields of business, law and policy where qualitative research methods are often used to examine real-life situations and set future directions. Case studies could provide a useful way to engage a much wider stakeholder community in ocean observing systems by presenting the data in very publicly accessible ways to enable the reader to apply the experience in his or her own real-life situation. The case study approach has the advantage of conveying a message to a wide range of stakeholders; either making scientists aware of potential new applications of their research; enabling users to understand the benefits of observations and information or to demonstrate the benefits to policy-makers in a real-life context.

To ensure that case studies are of value and not perceived as biased and non-scientific there is a need to develop a systematic approach to gathering information. Whilst the case studies presented here mostly provide anecdotal evidence as the importance of stakeholder engagement and partnerships in ocean observing only the case from Long Beach enumerates the monetary benefit which reinforces the views of Rayner et al. (2018) that there remains no comprehensive global attempt to value the social and economic benefits derived from ocean observations. It is therefore, recommended that a standard methodology is developed akin to the OECD (2016) protocol for measuring the ocean economy and adopted by the ocean observation community to build a consistent global view.

The key elements of the methodology are that it should create a consistent format for each user story that specifically describes the problem faced by the user; the commercial value of the problem faced by the user and/or cost expectations of the user; and, the delivery requirements. An important stakeholder will be the intermediary service providers (those organizations that take raw data and turn it into useable information for the user). The services may utilize new data services or be built on core services provided to support the ocean economy. In addition to a consistent methodology a common portal for best practice should be used – for example the central repository of best practice materials hosted through existing ocean best practice initiatives.

Better Understanding User Requirements

In addition to development of a methodology for building case studies and user stories, there is a need for sustained dialogue with users (intermediary users and end-users, as well as users from different domains and disciplines). What is essential that users have confidence in the observations, and consider that information provided is a valuable asset to their operations or policy- and decision-making. This could be achieved by addressing Service Level Agreements to provide the user with confidence in the reliable delivery of information, ensuring appropriate delivery methods are available to the user(s) demonstrating the veracity of the analytical approach using historical data prior to implementation in an operational environment and the creation of appropriate development, test and operational environments.

Asking users what they do (and how they do it), what decisions they make and what information they use to make decisions is in many cases more important than asking them about data and information needs. Producers and intermediary and end-users should work together to co-design and co-produce information and knowledge in an iterative and collaborative manner. It is important that all stakeholders involved in this process take ownership and accountability for the outcomes (Pagano and Volpin, 2001; Corringham et al., 2008).

Capacity Development and the Exchange of Knowledge

All the stakeholder case studies touch on the vital role that human capacity development plays in a successful integrated ocean observing system. This was particularly evident during Project Azul where one of the most important outcomes was the investment made in professional and academic training in operational oceanography. The lack of trained personnel is well recognized as a major obstacle to the development of ocean observing systems (Malone et al., 2014). A survey conducted by the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC of UNESCO, 2013) highlighted concerns related to capacity development in ocean observing[39] Some of these concerns included: an overdependence on project-oriented, short-term international support; training programs being mostly one-off with unsure long-term benefits; inadequate infrastructure inhibiting training programs, where they are most needed; lack of ship-based training programs (data collection/data handling); lack of a critical mass of ocean experts (both scientific and technical) and few mechanisms or incentives to retain built capacity and available experts; and, competition from non-marine sectors for new entrants and talent. The survey further

[39] http://unesdoc.unesco.org/images/0022/002268/226864e.pdf

demonstrated that problems are exacerbated in Small Island Development States (SIDS) and in particular in the Pacific Islands. The vastness of the ocean space and the remoteness of outer islands creates unique problems including a lack of vessels, which in turns hinders access to outer islands and create barriers to communication.

The UNDP (2009) highlights that there are four core principles that need to be addressed with regards to capacity development. These are: institutional arrangements; leadership; knowledge; and, accountability. Knowledge has traditionally been fostered at the individual level, mostly through education. But it can also be created and shared within an organization, such as through on-the-job training or even outside a formal organizational setting through general life experience, and supported through an enabling environment of effective educational systems and policies (UNDP, 2009).

Learned societies and professional bodies are uniquely placed to contribute to capacity development in ocean observing. Whilst often working in partnership, they are largely independent from government funding agencies, universities or science-based industries with their one of their primary objectives to provide opportunities for the exchange of ideas and practices to build capacity. Most are organized organically with regionally and specialist sub-networks with ever growing international memberships which allow capacity development based on international standards and ethical practices but cognizant of local needs. The independence of these bodies enables capacity development in an integrated way from working with early education providers to advising on policy at governmental and intergovernmental level.

Related to capacity it is essential that a gender perspective be integrated into all policies, plans and decision-making processes, including those related to risk assessment, early warning, information management, education and training (UNISDR, 2005, p. 4), capacity development, in general public awareness products, and in advocacy for ocean observing systems and their benefits. More gender-balanced representation within international and regional networks of experts should also be sought and the capacities of professional and other NGOs should be used as an enabler to do so.

Capacity development efforts in operational oceanography, including training programs, need to take a long-term perspective- and take advantage of existing regional network. Incentives for continuous updating of professional knowledge and sharing of expertise should be considered. Stakeholder engagement needs to include all those who stand to benefit from the enhanced capacity to ensure ownership and commitment to the process, and personally invested in its success.

Finally, hand in hand with capacity development is knowledge transfer. Knowledge transfer is essential to achieve effective dialogue and information exchange across the science–policy–society interface. As described in the EOOS case study, the use of knowledge brokers for ocean observation will be considered as a mechanism for stakeholder engagement and knowledge exchange and could be something that could be implemented wider across ocean observing systems.

Governance Design

The case studies presented all work under different governance models. It is important to consider governance in the optimization of the existing capacities and their usefulness, for design of new fit-for-purpose systems, as well as for engaging cross-disciplinary stakeholders in co-creation or co-financing. Governance structures will be varied depending on the needs and the starting point in each of the systems, system of systems, or framework design, however, a set of elements should be considered in all of them. Those elements consist (but aren't restricted to): stakeholder engagement, requirement gathering and feedback loop mechanisms; operational and organizational support to the processes; advisory and decision-making capacities; user interface. Effective communication, as previously described, should be a cross-cutting liaising element within the governance and vis-à-vis external stakeholders.

CONCLUSION

Stakeholder engagement and communication are critical to achieve sustained funding and truly reap the benefits of integration and joint prioritization in the field of ocean observation. Stakeholders play a fundamental role in building, evolving and sustaining integrated ocean observing systems. Stakeholders and users should be identified for each stage of the ocean observing framework design. Once stakeholders have been identified a process of selecting the most appropriate mechanisms for dialogue, buy-in, and co-design across stakeholder groups and communities should be developed. The evaluation and measurement of success is an essential component of any ocean observing system framework and may include a range of performance metrics, including cost-benefit analyses, stress tests and system experiments, pilot actions, as well as stakeholder consultation and engagement mechanisms. Ultimately, by engaging all stakeholders and creating successful partnerships there will be improved economic, societal and environment benefits realized from sustained integrated ocean observing systems.

AUTHOR CONTRIBUTIONS

This is a community white paper so is built out of a number of separate contributions. BM was white paper coordinator and lead author. BM, LC, LA, JH, NR, and JT were lead authors of community contributions. All others are contributing authors to each separate contribution.

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The Tropical Atlantic Observing System

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The tropical Atlantic is home to multiple coupled climate variations covering a wide range of timescales and impacting societally relevant phenomena such as continental rainfall, Atlantic hurricane activity, oceanic biological productivity, and atmospheric circulation in the equatorial Pacific. The tropical Atlantic also connects the southern and northern branches of the Atlantic meridional overturning circulation and receives freshwater input from some of the world's largest rivers. To address these diverse, unique, and interconnected research challenges, a rich network of ocean observations has developed, building on the backbone of the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA). This network has evolved naturally over time and out of necessity in order to address the most important outstanding scientific questions and to improve predictions of tropical Atlantic severe weather and global climate variability and change. The tropical Atlantic observing system is motivated by goals to understand and better predict phenomena such as tropical Atlantic interannual to decadal variability and climate change; multidecadal variability and its links to the meridional overturning circulation; air-sea fluxes of CO_2 and their implications for the fate of anthropogenic CO_2; the Amazon River plume and its interactions with biogeochemistry, vertical mixing, and hurricanes; the highly productive eastern boundary and equatorial upwelling systems; and oceanic oxygen minimum zones, their impacts on biogeochemical cycles and marine ecosystems, and their feedbacks to climate. Past success of the tropical Atlantic observing system is the result of an international commitment to sustained observations and scientific cooperation, a willingness to evolve with changing research and monitoring needs, and a desire to share data openly with the scientific community and operational centers. The observing system must continue to evolve in order to meet an expanding set of research priorities and operational challenges. This paper discusses the tropical Atlantic observing system, including emerging scientific questions that demand sustained ocean observations, the potential for further integration of the observing system, and the requirements for sustaining and enhancing the tropical Atlantic observing system.

Keywords: tropical Atlantic Ocean, observing system, weather, climate, hurricanes, biogeochemistry, ecosystems, coupled model bias

INTRODUCTION

Many developing countries surrounding the tropical Atlantic Ocean face societal challenges that are compounded by climate variability and change (**Figure 1**). Rainfall in South America and West Africa and Atlantic hurricanes are highly sensitive to conditions in the tropical Atlantic. These conditions are driven by complex interactions between the ocean, atmosphere, and land, and between other ocean basins and the tropical Atlantic. Strong and societally relevant variability occurs on seasonal to multidecadal timescales. The background state on which these fluctuations occur is changing, as are the two-way connections between the tropical Atlantic and the Pacific. In the tropical Atlantic Ocean, significant changes in physical and biogeochemical variables, including temperature, oxygen, nutrient availability and pH, are also occurring, and it is unclear how these changes will affect marine ecosystems and biodiversity. Short-term predictions and longer decadal and century-scale projections of the tropical Atlantic are made more challenging by persistent biases in climate models that have seen little progress over the past two decades.

The tropical Atlantic observing system has progressed substantially over the past 20 years (**Figure 2**), yet many challenges remain. Observing systems must continue to monitor the climate system and provide measurements to aid in weather and climate prediction, scientific research, and ocean state estimates. There are new emerging threats that will require additional scientific knowledge and monitoring capabilities. These include the increasing occurrence of weather and climate extremes and tipping points in ocean biogeochemistry and ecosystems. This paper summarizes the societal issues that demand tropical Atlantic climate monitoring and prediction, their scientific drivers, and the current observing system. It concludes with key recommendations for the future tropical Atlantic observing system.

SOCIETAL DRIVERS

Tropical Atlantic variability (TAV) influences a wide range of societally important phenomena on different timescales that span the physical, biogeochemical, and ecological systems and their interactions. This section summarizes the key societal drivers in the tropical Atlantic.

Rainfall

One of the most important climate- and weather-related societal drivers is continental rainfall. The impacts of tropical Atlantic

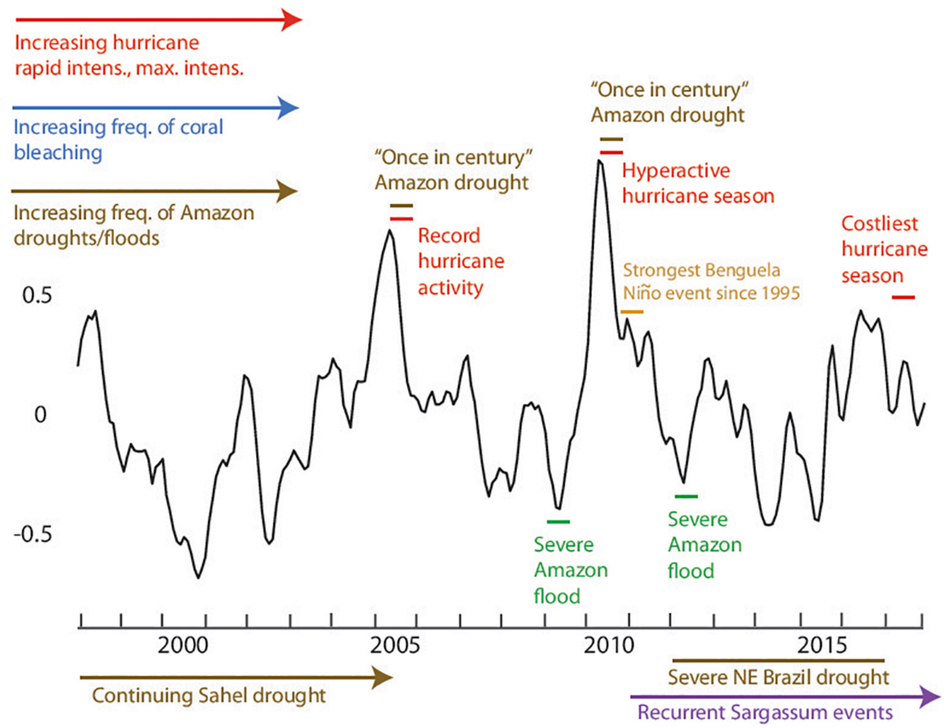

FIGURE 1 | Summary of notable tropical Atlantic societal impacts over the past 20 years. Black line is the monthly SST anomaly, relative to the 1998–2017 mean climatology, averaged between 5°N–25°N and 30°W–60°W.

climate variability on rainfall are strongest in South America and West Africa. The West African monsoon (WAM) brings most of the rainfall to West Africa during the year. Its onset is typically in late June or early July and it ends normally from late September to October (Sultan and Janicot, 2003). Knowledge of the development of the WAM is important for agricultural planning, as an unanticipated late onset and early demise of the monsoon can lead to crop failure. There is stronger interannual variability at the Guinea Coast compared to the Sahel, and rainfall anomalies often extend zonally across West Africa (Giannini et al., 2005), affecting large populations. A recent example is the 2011–2012 severe Sahel drought and famine, which was caused by below-normal and erratic rainfall in 2011 and poor harvests in 2011 and 2012[1].

The Sahel region also experiences strong rainfall variability on decadal and multidecadal timescales. There was a period of severe drought between the 1960s and 1980s that strongly impacted West African agriculture and economies. Rainfall in the Sahel has increased since the 1980s, but has not recovered to pre-drought levels (Nicholson et al., 2000; Dong and Sutton, 2015; Berntell et al., 2018). Through its impacts on soil moisture, vegetation, and albedo, the rainfall received during a given year affects the likelihood of drought the following year, acting to enhance decadal-multidecadal variations of Sahel rainfall (Zeng et al., 1999). The long-term trend of Sahel precipitation in response to the intensification of the hydrological cycle due to climate change is still unclear and may have significant consequences for West African populations (Druyan, 2011; Monerie et al., 2016).

The semiarid region of Northeast Brazil has also experienced strong rainfall variations and extreme droughts. This region is highly susceptible to drought because its short March–May rainy season is dependent on seasonal sea surface temperature (SST) and rainfall patterns in the tropical Atlantic. During 2011–2016, Northeast Brazil experienced its most severe and prolonged drought since 1981 (Brito et al., 2018). Prior to the recent drought period, Northeast Brazil experienced a severe flood in 2009 that has been linked to anomalous SSTs in the tropical Atlantic (Foltz et al., 2012). There is strong interannual and decadal variability of Northeast Brazil rainfall (Nobre and Shukla, 1996), along with a downward long-term trend of precipitation and increasing trend in air temperature (Lacerda et al., 2015).

During the years 2005–2012, the Amazon region experienced some of the most severe droughts and floods in its recorded history. The two record droughts of 2005 and 2010 were regarded as "once in a century" climate extremes at the times of their occurrences and were linked to anomalous SSTs in the tropical Atlantic (**Figure 1**; Marengo et al., 2008; Zeng et al., 2008; Lewis et al., 2011). The droughts occurred during the dry season (June–September), when the ecosystem is particularly vulnerable to stressors. Normally the Amazon is a carbon sink, absorbing CO_2 from the atmosphere. However, during 2005–2008 the Amazon was a net carbon source due to drought-stressed and dying trees, combined with increased occurrence of fires (Zeng et al., 2008;

[1]https://news.un.org/en/story/2012/05/411752-un-relief-coordinator-warns-over-humanitarian-crisis-africas-drought-hit-sahel

Yang et al., 2018). At the other extreme, the Amazon floods of 2009 and 2012 were the largest going back several decades (Satyamurty et al., 2013; Filizola et al., 2014) and left hundreds of thousands homeless. Since the 1970s there has been an upward trend in the year-to-year variability of Amazon River discharge, following a period with no trend during 1904 through the 1960's (Satyamurty et al., 2013; Barichivich et al., 2018). It is unclear whether the recent increase in variability is part of a longer trend driven by climate change or due to natural variability.

In summary, there is a strong societal need for accurate predictions of rainfall to improve agricultural productivity, allow for more efficient use of water resources, and protect homes and infrastructure against floods. There is also a need to mitigate disease outbreaks, which commonly occur following large floods. Rainfall predictions are needed on many different climate timescales, ranging from intraseasonal to multidecadal. Climate change projections of rainfall and the occurrences of droughts, floods, and extremes in rainfall intensity are also a necessity for developing countries surrounding the tropical Atlantic Ocean.

Tropical Cyclones

Tropical cyclones (TCs) are one of the deadliest and most destructive hazards in the tropics and subtropics. Threats include storm surge, damaging winds, and inland flooding from rainfall. Developing countries and low-lying coastal areas are particularly vulnerable. Since 2005, there have been eight Atlantic hurricanes that have resulted in at least $25 billion in damages, including Harvey, Irma, and Maria in 2017 and Florence in 2018[2,3]. Adjusted for inflation, 9 of the 10 costliest hurricanes have occurred since 2004. The increasing destruction is likely a result of coastal population growth in the United States as well as natural and human-induced changes in the large-scale hurricane environment that can influence TC intensity, rapid intensification (RI), translation speed, and rainfall (Goldenberg et al., 2001; Knutson et al., 2010; Kossin, 2017; Scoccimarro et al., 2017; Balaguru et al., 2018; Kossin, 2018; Wang et al., 2018).

The Atlantic basin as a whole has experienced large variations in TC activity on interannual and longer timescales. The 2005, 2010, and 2017 Atlantic hurricane seasons were extremely active, with 28, 19, and 17 cyclones of at least tropical storm strength, respectively. The 2005 and 2017 seasons were the costliest on record at the time of occurrence. There has also been significant decadal-multidecadal variability of TC activity in the Atlantic, with above-normal activity during the 1940s and 50s, below-normal from the 60s to the early 90s, and above-normal since the mid-90s (Goldenberg et al., 2001). The magnitude of hurricane RI (increase in maximum wind speed of at least 25 kt in 24 h) has increased in the central and eastern tropical Atlantic since the 1980s (Balaguru et al., 2018). Whether a storm will undergo RI is particularly difficult to predict (Kaplan et al., 2010). When RI occurs before landfall, destruction and loss of life can be catastrophic.

Ultimately, in terms of seasonal prediction, what matters most for coastal residents and planning agencies is the number and severity of land-falling TCs. There have been marked changes in Atlantic land-falling TCs in the past several decades (Wang et al., 2011; Kossin, 2017). However, the number of landfalling TCs is very difficult to predict. There are indications that TC activity and intensification before landfall may be increasing in the Atlantic due to global warming (Emanuel, 2005, 2017; Webster et al., 2005; Elsner et al., 2008).

In summary, there is a need for improved intraseasonal and seasonal predictions of TC activity, including landfalls, and more reliable decadal-multidecadal projections. There are also uncertainties related to how Atlantic TC activity will change in response to global warming. This is particularly important for highly populated low-lying coastal areas in the southeastern United States, which will likely become more susceptible to storm surge inundation as sea level rises. Improved intraseasonal and seasonal predictions and longer-term projections will allow coastal communities to prepare and allocate resources for post-storm recovery.

Biogeochemistry

One of the important unknowns in the future global carbon budget is the extent to which the ocean sink keeps pace with anthropogenic CO_2 emissions. Present-day observations and models show that the ocean sink has increased along with CO_2 emissions and is currently absorbing about 28% of anthropogenic CO_2 emissions annually (Le Quéré et al., 2018). The amount of CO_2 that can be emitted by fossil fuel burning and industrial uses while limiting global surface temperature rise to within 2°C and stabilizing atmospheric CO_2 levels is critically dependent on the magnitude of this ocean sink[4]. The tropical Atlantic is the second largest source, after the tropical Pacific, of oceanic CO_2 to the atmosphere, releasing about 0.10 Pg C yr^{-1} in the 18°S–18°N region (Landschützer et al., 2014). While uptake of anthropogenic CO_2 by the ocean regulates the atmospheric CO_2 concentration, it also leads to ocean acidification, with significant but poorly understood consequences for marine organisms and ecosystems (Feely et al., 2004; Bates, 2007). Carbon trends remain unclear because of short records and high natural variability in the tropical Atlantic, though there are indications of significant decadal variations that have implications for anthropogenic CO_2 uptake (Park and Wanninkhof, 2012). There is also significant interannual variability of air-sea CO_2 fluxes in the tropical Atlantic that is closely linked to climate variability (Lefèvre et al., 2013; Ibánhez et al., 2017).

Oxygen minimum zones (OMZs) are found at intermediate depths (100–900 m) in the eastern tropical oceans off the equator (Karstensen et al., 2008). The OMZs in the eastern tropical Atlantic are split into shallow (100 m) and deep (400 m) branches (Monteiro et al., 2008; Brandt et al., 2015) that are caused primarily by enhanced biological productivity/consumption and sluggish ventilation, respectively. The shallow OMZs overlap with the euphotic zone and hence have a direct impact on ecosystems, carbon export, and the release of CO_2 and other climate-relevant trace gases like N_2O to the atmosphere. Since

[2]https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf

[3]https://en.wikipedia.org/wiki/List_of_costliest_Atlantic_hurricanes

[4]https://unfccc.int/process/conferences/pastconferences/paris-climate-change-conference-november-2015/paris-agreement

the 1960's the OMZs in the eastern tropical Atlantic have been expanding (Stramma et al., 2008; Brandt et al., 2015), with far-reaching consequences for tropical ecosystems (Stramma et al., 2012; Gilly et al., 2013), nutrient cycling and resilience, as well as goods and services, including food production through fisheries and aquaculture, ecosystem conservation, and climate regulation (Diaz and Rosenberg, 2008; Stramma et al., 2012; Craig and Bosman, 2013; Kalvelage et al., 2013; Martinez-Rey et al., 2015; Arevalo-Martinez et al., 2015).

The carbon and oxygen cycles and ecosystems in coastal regions are influenced by river outflow and upwelling. The tropical Atlantic receives about 25% of the global riverine freshwater discharge from three large rivers (Amazon, Congo, and Orinoco; Dai and Trenberth, 2002). The rivers also deliver high loads of nutrients, which lead to high oceanic productivity near the river mouths. The tropical Atlantic includes two major eastern boundary upwelling systems that support some of the world's most productive fisheries: the Canary and the Benguela (Chaigneau et al., 2009). These systems are particularly vulnerable to ongoing warming, deoxygenation and acidification (Gruber, 2011). It is important to understand what drives biological production within these regions in order to understand ecosystem dynamics and also to constrain the regional and global carbon cycles. There are several important factors that control biological production in eastern upwelling regions, including along-shore winds, eddy activity, and mixed layer depth (Lachkar and Gruber, 2012). Close to coastal areas, high productivity and local oxygen depletion are found, with concentrations below 30 μmol kg^{-1}, and intense respiration and remineralisation, associated with high organic matter input, has been observed (Chen and Borges, 2009). Anoxic conditions regularly occur at the Namibian shelf (Brüchert et al., 2006; Mohrholz et al., 2008) and have been found more recently at the Senegalese shelf (Machu et al., 2019) and within mesoscale eddies (Karstensen et al., 2015; Schütte et al., 2016b). Low oxygen conditions affect the carbon cycle, ecosystems and fisheries. Trace elements (e.g., Zn, Fe, Co, and Mn) affect biomass and the turnover rate of phytoplankton, and ultimately the productivity of entire food webs. The cycling of these micronutrients is thus critically linked to carbon cycling.

Ecosystems and Pollution

Many coastal communities surrounding the tropical Atlantic Ocean rely on seafood for sustenance. The importance of fisheries in the tropical Atlantic can be demonstrated most easily by the total catch and dependence on the region. Approximately 10 million tons of seafood (from 87.2 million tons of global marine capture production) were harvested in the Central and South Atlantic in 2016[5]. The fishing sector is also very important in tropical Atlantic coastal countries. There are 8 million fishers in Africa, Latin America, and the Caribbean, though not all of them are operating in the Atlantic; many foreign fleets (Korean, Chinese, Russian, European) also use tropical Atlantic resources. Threats to fisheries include overfishing, pollution, and invasive species.

The frequency of marine heatwaves has increased significantly in the tropical North Atlantic during the past 35 years and is expected to increase further in response to global warming (Oliver et al., 2018). Marine heatwaves are defined as anomalously warm SST that lasts for five or more days, with temperatures warmer than the 90th percentile based on a 30-year historical baseline period (Hobday et al., 2016). They can have detrimental effects on marine organisms, including coral bleaching, disease outbreaks, and forced migration (Comte and Olden, 2017; Hughes et al., 2018). Future responses of marine organisms to climate change and the implications for the biogeochemical cycles and fisheries are unclear.

Since 2011, there has been an increase in the abundance of Sargassum in the western tropical North Atlantic, often resulting in mass "beaching" events in the Caribbean (Wang and Hu, 2017) and also in western Africa and Brazil. These events can have significant negative impacts on local economies and ecology (Hu et al., 2016). It is unclear what has caused the increase in Sargassum in the western tropical North Atlantic and Caribbean. Hypotheses include changes in upper-ocean temperature and nutrients or anomalous winds and ocean currents. Previous events such as the Deepwater Horizon drilling rig explosion can also have serious negative consequences for local ecosystems and economies and require knowledge of the ocean circulation.

Transport and fishing vessels in the Atlantic are sources of marine pollution such as plastics, hydrocarbons, and particulate materials. Overall, there are relatively few records of pollutants that have emissions high enough to cause harmful consequences in the open ocean. Mercury and plastic pollution, nevertheless, show us that adverse effects of those pollutants in marine ecosystems can be widespread. Plastic is a pervasive pollutant of high concern. Its use has increased 20 times in the past 50 years and is expected to double in the next 20 years[6]. A high amount of plastic materials escapes collection systems, generating significant risks for marine biota. Their threats to marine life are primarily mechanical, due to ingestion of plastics and entanglement (Derraik, 2002). It has also been shown that contaminants from plastic debris may leach into seawater or be ingested by marine organisms (Romera-Castillo et al., 2018), creating a new risk route.

Ecosystems are highly dependent on nutrient availability and biogeochemistry, which themselves are closely linked to the physical state of the ocean. There is a strong need to monitor fish stocks and understand their variability and response to internal and external stressors. External threats include overfishing, invasive species, global warming, deoxygenation, and pollution. Observations are needed for monitoring and scientific understanding, and models that incorporate biogeochemistry and ecosystems are critical for informing scientists and policy-makers of future changes to tropical Atlantic ecosystems.

[5]http://www.fao.org/fishery/statistics/global-capture-production/en

[6]https://www.ellenmacarthurfoundation.org/assets/downloads/EllenMacArthurFoundation_TheNewPlasticsEconomy_Pages.pdf

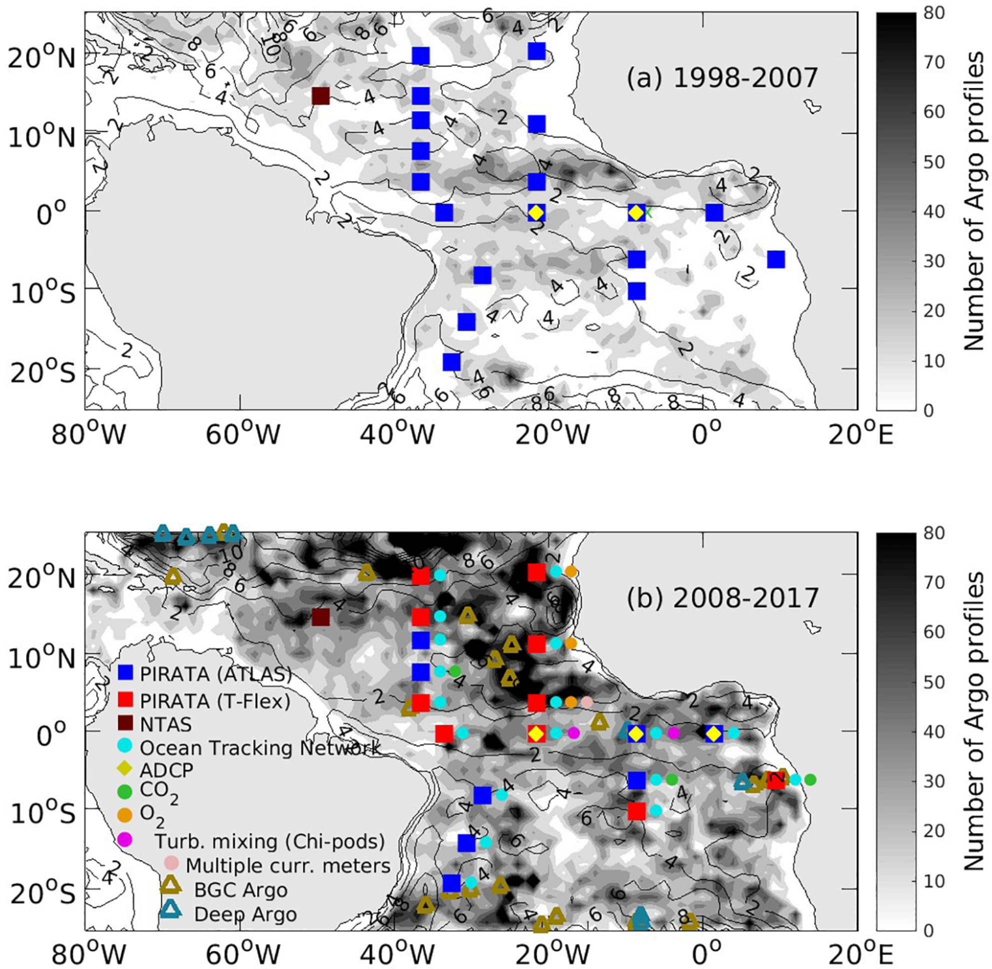

FIGURE 2 | Key elements of the tropical Atlantic *in situ* observing system during **(a)** 1998–2007 and **(b)** 2008–2017. Gray shading represents the number of Argo profiles made in each 1° box. Contours show the average number of hourly surface drifter observations made in each 1° box per month. Squares show moored buoy locations, circles indicate additional measurements made from the moorings, and triangles show locations of deep Argo and biogeochemical Argo floats during September 2018.

SCIENCE DRIVERS

This section summarizes the key scientific phenomena and processes that affect the societally relevant issues presented in the previous section.

Modes of Variability and Tropical Cyclones

Many societally relevant phenomena in the tropical Atlantic region, such as droughts, floods, TCs, and marine heat waves, are linked to TAV. TAV involves coupled ocean-atmosphere processes and their interactions, most notably, fluctuations of the trade winds, SST, and rainfall (**Figure 3**; Xie and Carton, 2004). There is also significant external forcing of TAV from ENSO, the North Atlantic Oscillation, and the South Atlantic Anticyclone (Enfield and Mayer, 1997; Czaja et al., 2002; Chang et al., 2006; Illig and Dewitte, 2006; Lübbecke et al., 2010; Lübbecke and McPhaden, 2012). Interannual variability of the tropical Atlantic can be described in terms of two main climate modes: the Atlantic Zonal Mode (AZM) and the Atlantic Meridional Mode (AMM). The AZM, also commonly referred to as the Atlantic Niño and Atlantic equatorial mode, is associated with SST anomalies near the equator, peaking in the eastern basin (Zebiak, 1993; Polo et al., 2008; Lübbecke et al., 2018), while the AMM is characterized by a cross-equatorial gradient of SST and wind anomalies (Ruiz-Barradas et al., 2000; Chiang and Vimont, 2004). Their patterns and seasonality are depicted in **Figure 4**.

On interannual timescales, the AZM affects the WAM (Sultan and Janicot, 2003; Polo et al., 2008; Losada et al., 2010; Nicholson, 2013). A warm phase of the AZM shifts the intertropical convergence zone (ITCZ) anomalously to the south during June–August, increasing rainfall over the Gulf of Guinea (**Figure 4A**; Janicot et al., 1998; Okumura and Xie, 2004; Polo et al., 2008; Joly and Voldoire, 2010; Losada et al., 2010; Rodríguez-Fonseca et al., 2011, 2015). A positive AZM is also

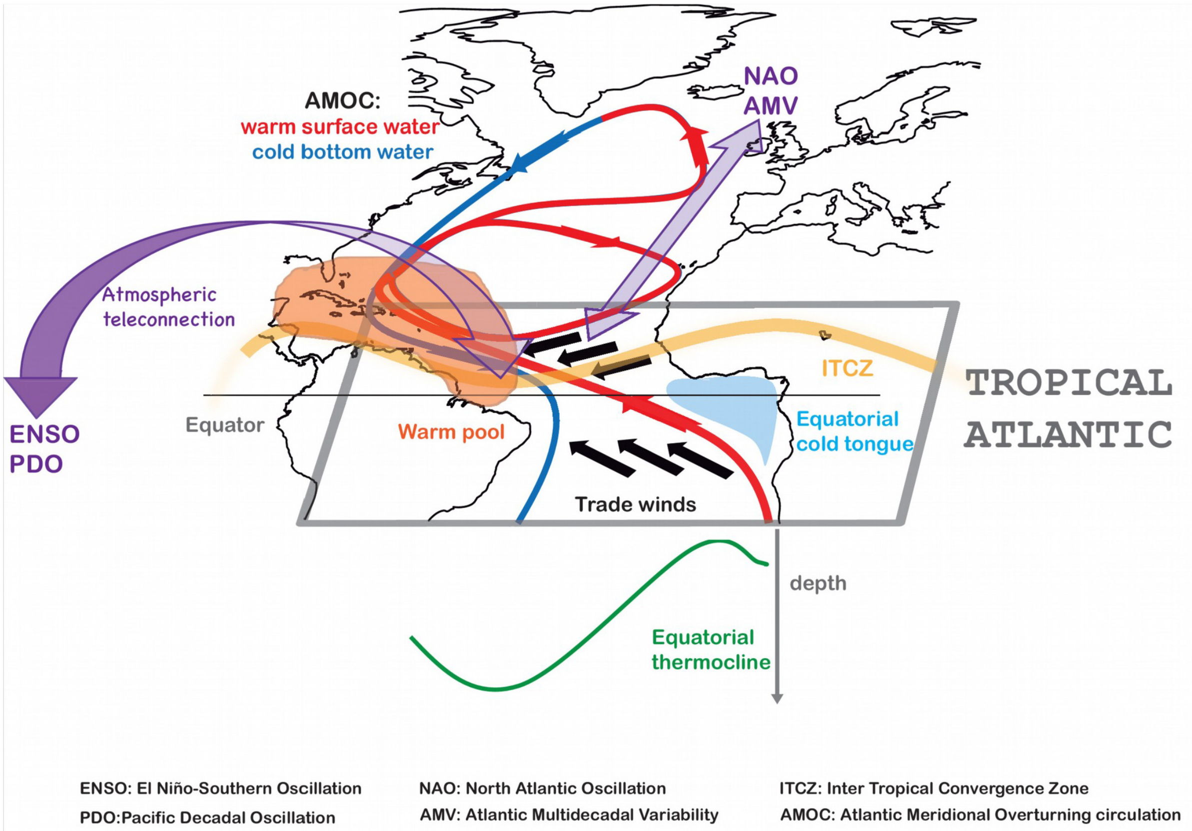

FIGURE 3 | Schematic of the key components for understanding tropical Atlantic variability.

associated with a late onset of the WAM, though eastern tropical North Atlantic SST also plays a role (Brandt et al., 2011a). An earlier development of a warm phase of the AZM can enhance the southward migration of the ITCZ, bringing excess rainfall to the Brazilian Amazon and Northeast Brazil (Torralba et al., 2015). The tropical Pacific also influences rainfall in these regions (Moron et al., 1995; Nobre and Shukla, 1996; Janicot et al., 2001; Rowell, 2001) and affects the AZM (Chang et al., 2006).

A positive AMM favors an earlier migration of the ITCZ northward during April–May, shortening the rainfall season over the Amazon region and Brazilian Northeast and leading to severe droughts over the Northeast (**Figures 4B,C**; Nobre and Shukla, 1996; Hastenrath, 2006; Kucharski et al., 2008; Liebmann and Mechoso, 2011; Rodrigues et al., 2011). The opposite is generally true for negative AMM phases (Foltz et al., 2012; Rodrigues and McPhaden, 2014). There is a strong relationship between the AMM and Atlantic hurricane activity (Kossin and Vimont, 2007) due to the AMM's influence on SST, position of the ITCZ, strength of vertical wind shear, and humidity (DeMaria and Kaplan, 1994).

Atlantic Multidecadal Variability (AMV; Kerr, 2000) modulates Sahel rainfall through its control of the Atlantic ITCZ (Knight et al., 2006; Zhang and Delworth, 2006; Mohino et al., 2011; Dieppois et al., 2015). There is also strong evidence linking decadal-multidecadal tropical Atlantic SST variability to hurricane activity (Goldenberg et al., 2001; Latif et al., 2007; Balaguru et al., 2018), but the drivers of this SST variability are not well known (Yang, 1999; Chang et al., 2000; Tanimoto and Xie, 2002; Evan et al., 2011; Booth et al., 2012; Clement et al., 2015). Several studies have demonstrated that there is potential for improved seasonal predictions of hurricane landfall frequencies and intensities if the predicted atmospheric steering flow, wind shear, and SST patterns are taken into account (Wang et al., 2011; Kossin, 2017), further emphasizing the importance of tropical Atlantic SST variations and their interactions with the atmosphere.

The influence of interannual TAV on the West African and South American monsoons is not stationary and can be modulated by its interactions with variability from other tropical oceans (Losada et al., 2012; Torralba et al., 2015). TAV also has robust imprints on global climate. The AZM impacts the Indian summer monsoon (ISM), altering the ENSO-ISM connection (Kucharski et al., 2007, 2008; Wang et al., 2009; Barimalala et al., 2012, 2013). Summer equatorial variability associated with the AZM is also highly correlated with the next winter's ENSO (Polo et al., 2008; Rodríguez-Fonseca et al., 2009; Ding et al., 2012; Keenlyside et al., 2013; Martín-Rey et al., 2015). The AZM-ENSO relationship is strongest during negative AMV phases (Martín-Rey et al., 2014; Polo et al., 2015a), when equatorial Atlantic SST variability is enhanced (Martín-Rey et al., 2018). A possible

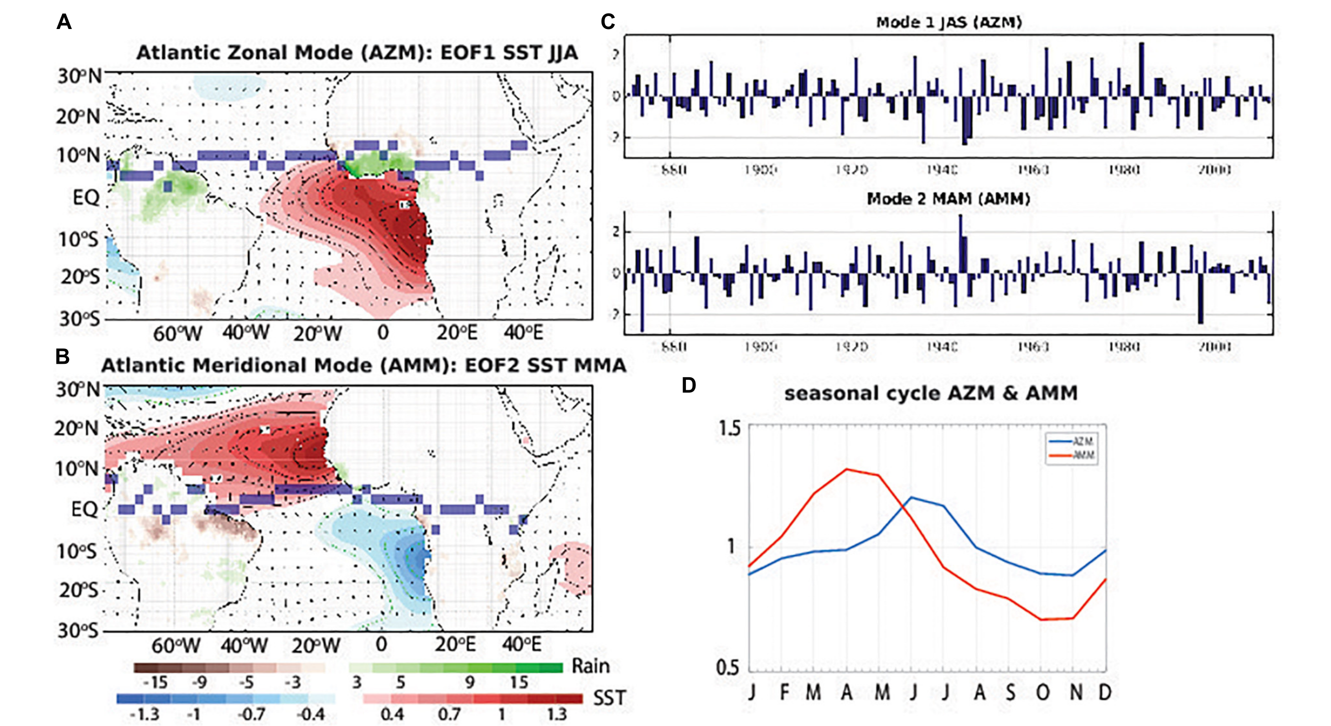

FIGURE 4 | Leading modes of tropical Atlantic SST variability. Shown are the composites of events characterized by a principal component value > 1 standard deviation, minus those events in which the principal component has values < −1 standard deviation. The modes are calculated from Had-SST data (°C) using an 11-year high pass filter. **(A)** Composite of the leading mode in June–July–August for SST (shading over ocean), rainfall in cm mo^{-1} from University of Delaware (shading over land; data are available from http://climate.geog.udel.edu/~climate/html_pages/Global2011/README.GlobalTsP2011.html), and surface wind from NCEP 20th Century Reanalysis. **(B)** As in panel **(A)** but for the second mode. Purple shading in panels **(A)** and **(B)** indicates the seasonal mean position of the ITCZ. **(C)** Interannual times series of the first and second EOF modes. **(D)** Evolution of the standard deviation of the leading EOF (blue) and second EOF (red) corresponding to the Atlantic Zonal Mode (AZM) and Atlantic Meridional Mode (AMM), respectively.

connection between the tropical North Atlantic and tropical Pacific variability has also been suggested (Wu et al., 2007; Ham et al., 2013a,b; Wang et al., 2017), and it seems to be more active during positive AMV phases (Wang et al., 2017). However, global warming may also affect this teleconnection (Dong and Zhou, 2014; Liu and Sui, 2014). Improved understanding of interactions between the tropical oceans is needed to advance seasonal to decadal climate predictions and climate change projections (Cai et al., 2019). Sustained observations in the tropical Atlantic are a key requirement for achieving this goal.

Despite significant progress in understanding TAV and its impacts during the last decades, many open questions remain. Dynamical mechanisms for the generation of the AZM (Keenlyside and Latif, 2007; Polo et al., 2015b; Jouanno et al., 2017) have been questioned and, mostly based on model simulations, important roles for thermodynamic processes proposed (Nnamchi et al., 2015, 2016). The importance of thermodynamic forcing is likely amplified in models with enhanced SST bias (Jouanno et al., 2017). Advection and equatorial deep jets (EDJ; vertically alternating zonal currents) also affect the AZM (Brandt et al., 2011b; Richter et al., 2013).

Another open question concerns the relationship between the AZM and other modes of climate variability in the tropical Atlantic. Warm events that occur in the southeastern tropical Atlantic off Angola and Namibia have been termed Benguela Niños (Shannon et al., 1986). They have a pronounced impact on fisheries in coastal areas (e.g., Boyer and Hampton, 2001) and rainfall over south-western Africa (Rouault et al., 2003). SST anomalies in the eastern equatorial to subtropical South Atlantic that covary with anomalies of opposite sign in the southwestern subtropical South Atlantic have been described as the South Atlantic Ocean Dipole (SAOD, Venegas et al., 1996; Morioka et al., 2011; Nnamchi et al., 2011, 2016; Rouault et al., 2018). In addition to having similar climatic impacts on adjacent continents as the AZM, the SAOD has been linked to the Antarctic Oscillation and rainfall anomalies over the southern parts of Africa and South America (Nnamchi et al., 2011; Morioka et al., 2011, 2014). The Benguela Niño and SAOD have been linked to the AZM (Lübbecke et al., 2010; Richter et al., 2010; Nnamchi et al., 2016, 2017; Rouault et al., 2018), but it is unclear whether the Benguela Niño and AZM are part of the same climate mode or closely related but distinct modes (Polo et al., 2008; Goubanova et al., 2013; Bachèlery et al., 2016a,b; Illig et al., 2018a,b; Illig and Bachèlery, 2019). Intraseasonal wind bursts seem to play an important role in AZM evolution during some years (Marin et al., 2009; Herbert and Bourlès, 2018). The AZM has been shown to impact surface chlorophyll-a concentration in the eastern equatorial

Atlantic (Grodsky et al., 2008), but its broader effect on primary productivity is still unknown.

Other key questions relate to the nature and importance of specific SST feedbacks onto the atmosphere. Bjerknes and wind-evaporation-SST feedbacks in particular are considered to be essential elements of the AZM and AMM, respectively. Both feedbacks involve the horizontal adjustment of the sea level pressure gradients to SST gradients (Lindzen and Nigam, 1987; Young, 1987). However, they are complicated by other factors such as the vertical adjustment of the planetary boundary layer to SST (Sweet et al., 1981; Hayes et al., 1989; Wallace et al., 1989) and the effects of higher atmospheric levels on surface pressure (Richter et al., 2014a; Diakhaté et al., 2016).

There are many open questions regarding the way the spatial patterns of the SST modes (Losada and Rodríguez-Fonseca, 2016), their interactions with the extratropical Atlantic and other tropical basins (Czaja et al., 2002; Losada et al., 2012), and changes in the climatological background states can affect rainfall regimes (Suarez-Moreno and Rodríguez-Fonseca, 2018) and TC activity (Latif et al., 2007; Vecchi and Soden, 2007; Kossin, 2017). There is still a lot of uncertainty with respect to the air-sea interactions linking the AZM and AMM (Servain et al., 1999; Andreoli and Kayano, 2003; Foltz and McPhaden, 2010a,b; Richter et al., 2013, 2014a; Burmeister et al., 2016) and the processes responsible for the AMM, including its relation to coastal and open-ocean upwelling (Doi et al., 2009; Evan et al., 2011; Foltz et al., 2012; Rugg et al., 2016).

Tropical cyclones are strongly influenced by the underlying SST, which in turn is affected by TAV. TCs also typically induce a cold wake of upper-ocean temperatures that can provide a negative feedback on their intensities. The strength of the feedback depends on a storm's intensity and translation speed as well as the ocean heat content and salinity structure, which vary regionally and on seasonal to multidecadal timescales (Shay et al., 2000; Balaguru et al., 2012, 2015, 2018). This is especially true in the northwestern tropical Atlantic, where the Amazon-Orinoco plume increases salinity stratification, limiting hurricane-induced SST cooling (**Figure 5**; Balaguru et al., 2012; Grodsky et al., 2012b; Domingues et al., 2015). The impact of interannual to multidecadal changes in upper-ocean temperature and salinity stratification on TCs' cold wakes and intensities has only begun to be explored (Huang et al., 2015; Balaguru et al., 2016). A complicating factor in the study of TAV and TC activity is that some of the largest SST biases in global climate models occur in this region (see section "Predictability and Model Biases").

All of the aforementioned climate variations occur in a changing climate. Significant trends in tropical Atlantic SST, surface salinity, upper-ocean heat content, winds, cloudiness, and rainfall have emerged in the past decade (Tokinaga and Xie, 2011; Durack et al., 2012; Servain et al., 2014). It is unclear how these changes are affecting continental rainfall and the frequencies of droughts and floods (Elsner et al., 2008; Trenberth et al., 2014). There is robust forcing of the tropical Atlantic from the tropical Pacific on interannual and longer timescales (Enfield and Mayer, 1997; Chiang et al., 2002; Villamayor and Mohino, 2015). These teleconnections are likely to change with the varying mean states of the Pacific and Atlantic. The frequency of extreme El Niño and La Niña events is likely to increase (Cai et al., 2014, 2015a,b), which will affect the tropical North Atlantic ocean-atmosphere system. An improved understanding of TAV and its interactions with a warming climate can also potentially improve ENSO seasonal forecasts (Keenlyside et al., 2013; Martín-Rey et al., 2015; Dommenget and Yu, 2017). There is growing evidence that Atlantic hurricane activity will be affected by climate change (Grossmann and Morgan, 2011; Walsh et al., 2016; Sobel et al., 2016). Theory and numerical models predict that as SST rises, the maximum potential intensity that storms can reach will increase, enabling more powerful hurricanes (Emanuel, 1999; Elsner et al., 2008). Climate models predict increases in wind shear in some portions of the Atlantic hurricane development region (Latif et al., 2007; Vecchi and Soden, 2007), which would, however, act to decrease overall Atlantic storm activity.

Observational needs for tropical Atlantic modes of variability and TCs include long data records of upper-ocean and near-surface atmospheric parameters. These are required for improved understanding, monitoring, and predictability on seasonal to multidecadal timescales, including global warming. Of particular importance are dense measurements in the oceanic mixed layer and of air-sea heat, moisture, and momentum fluxes. The northwestern and southeastern tropical Atlantic should be high priority regions for additional measurements because of their importance for TCs and the equatorial Atlantic modes of variability, respectively.

Processes That Affect Upper-Ocean Temperature and Salinity

It is essential to understand and monitor changes in tropical Atlantic SST and near-surface salinity in order to advance understanding of the climate system, improve models, and address many of the outstanding societal challenges described in Section "Societal Drivers". The tropical Atlantic seasonal cycle, TAV, and TC activity are driven to a large extent by changes in SST. Upper-ocean salinity affects vertical mixing and SST (Breugem et al., 2008; Balaguru et al., 2012) and is an important indicator of changes in the hydrological cycle (Durack et al., 2012). Many of the processes that control near-surface temperature and salinity (vertical mixing, air-sea fluxes) also drive variations of biogeochemical quantities such as CO_2, O_2, and nutrients. These parameters are discussed only briefly here and in more detail in Section "Biogeochemistry, Ecosystems, and Pollution".

Observational and modeling studies of the equatorial mixed layer heat balance have demonstrated the importance of vertical turbulent mixing for generating seasonal cooling of SST in the equatorial Atlantic (Foltz et al., 2003; Peter et al., 2006). Progress has been made identifying processes responsible for the seasonal cycle of vertical turbulent mixing such as shear from the background currents, intraseasonal tropical instability waves (TIWs) and wind-driven waves, and the diurnal cycle in the mixed layer (Foltz et al., 2003; Jouanno et al., 2011; Giordani et al., 2013; Hummels et al., 2013; Wenegrat and McPhaden, 2015; Scannell and McPhaden, 2018). Away from

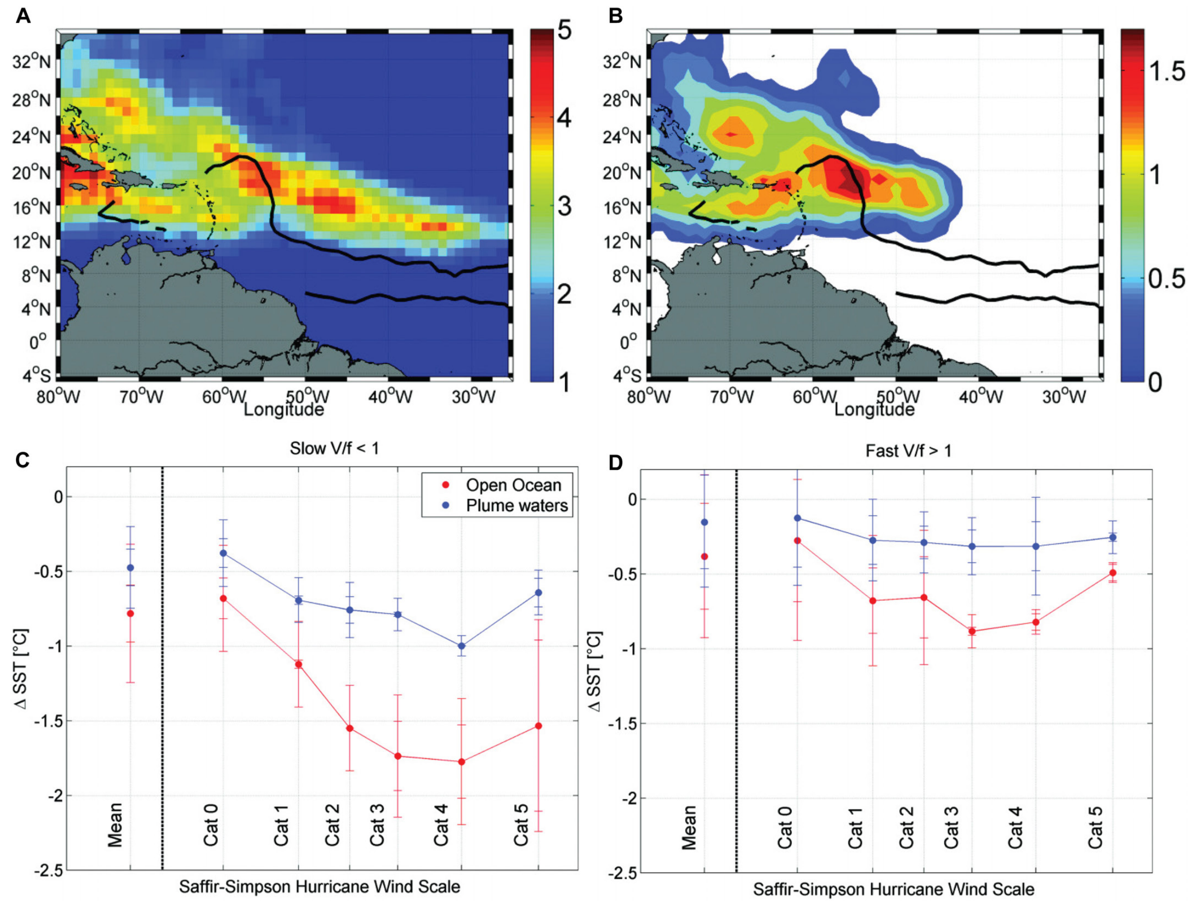

FIGURE 5 | The number of 1950–2010 "best track" TCs per 1° box (smoothed by a 3° × 3° block average) **(A)** that evolve as categories 4 and 5 somewhere along their path and **(B)** that intensified locally to categories 4 and 5. The black curve shows the historical extent of the Amazon–Orinoco river plume during the hurricane peak season (August to October). **(C,D)** Mean sea surface cooling induced by North-Atlantic hurricanes as a function of the Saffir-Simpson wind scale, with error bars showing the 90 and 95% significance levels. Responses estimated over open ocean waters (red dots) are distinguished from those evaluated within the historical plume region (blue dots). **(C)** Slow-moving (or low latitude) tropical cyclones with $V/f < 1$ (V is translation speed and f is Coriolis parameter), **(D)** fast moving (or high-latitude) storms with $V/f > 1$. Adapted from Reul et al. (2014).

the equator, surface heat fluxes play a more dominant role (Nobre et al., 2012; Foltz et al., 2013, 2018; Cintra et al., 2015; Nogueira Neto et al., 2018). However, there remain significant seasonal variations in the heat budget residuals (i.e., changes in mixed layer heat content that cannot be explained by the net surface heat flux) at some off-equatorial locations, implying that vertical mixing and other processes may be important (**Figure 6**; Foltz et al., 2018). The residuals are particularly large in eastern upwelling regions, consistent with previous studies (Foltz et al., 2013; Faye et al., 2015; Scannell and McPhaden, 2018). Outside of upwelling regions, there is evidence that near-inertial wave-induced mixing can have a significant impact on SST (Jochum et al., 2013). There is debate about the impact of salinity stratification on vertical mixing and SST in the Amazon-Orinoco River plume region of the northwestern tropical Atlantic (Balaguru et al., 2012; Hernandez et al., 2016). An ongoing challenge is to correctly represent ocean-wave-atmosphere coupling, which is important because of its impacts on turbulent heat and momentum fluxes (Belcher et al., 2012; Qiao et al., 2016; Reichl et al., 2016; Aijaz et al., 2017; Stoney et al., 2017; Bruneau et al., 2018). The parameterizations used in coupled climate and hurricane forecast models often have not been confirmed by observations. Uncertainties remain in large part because of very few long time series (one year or longer) of vertical mixing and its driving forces (e.g., current shear, temperature and salinity stratification) at off-equatorial locations.

One major difference between the mixed layer heat and salinity budgets is that for the salinity budget, horizontal advection is generally much more important (Foltz and McPhaden, 2008; Da-Allada et al., 2013, 2017; Camara et al., 2015). This is due to multiple factors, including stronger spatial gradients of the surface freshwater flux due to precipitation and river outflow and the fact that sea surface salinity (SSS) anomalies are not damped by the atmosphere, in contrast to SST anomalies. On interannual timescales, there is some evidence that changes in ocean circulation dominate in the western tropical Atlantic (Coles et al., 2013; Foltz et al., 2015). However,

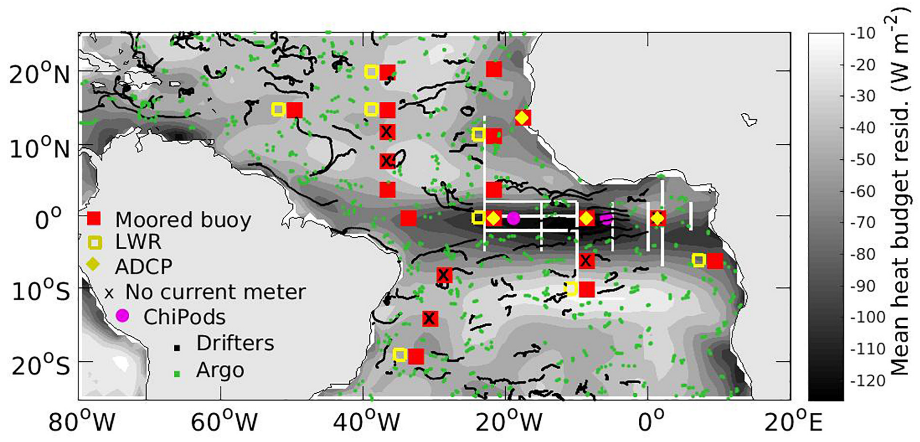

FIGURE 6 | Elements of the mixed layer heat budget and vertical mixing observing system. Black trajectories show the tracks of all surface drifters during August 2018. Green dots indicate locations of Argo floats in August 2018. Yellow squares and diamonds show mooring locations with longwave radiation sensors and ADCPs, respectively. Purple circles indicate locations with turbulence measurements, and a black 'x' indicates that the mooring does not have a near-surface current meter. Shading shows the annual mean heat budget residual (2003–2017), an estimate of the sum of horizontal heat advection and vertical turbulent cooling, calculated using TropFlux surface heat fluxes, blended satellite microwave-infrared SST, and mixed layer depth calculated from monthly gridded EN4 ocean temperature and salinity. White lines show the locations of ship-based and glider-based microstructure measurements conducted during 2005–2011.

interannual variations in Amazon outflow can also contribute (Zeng et al., 2008). The balance between ocean dynamics and changes in Amazon discharge is still not well understood. For example, the Amazon plume covered less area during the Amazon flood year of 2012 than in 2011 (Grodsky et al., 2014).

Turbulent mixing in the upper thermocline above the upper continental slopes and shelves of the eastern boundary upwelling regions is a dominant process bringing colder, nutrient-rich water from the deeper ocean to the surface mixed layer. Mixing is enhanced due to tide-topography interaction that largely sustains the elevated productivity in the Atlantic's eastern boundary upwelling regions (Schafstall et al., 2010). In the deeper thermocline away from continental margins and varying topography, turbulent mixing processes are weak. Nevertheless, about 30% of the oxygen consumed in the OMZs of the eastern tropical Atlantic is replenished by interior ocean mixing processes sustained through internal wave-wave interaction (Brandt et al., 2015).

Since direct measurements of surface heat fluxes are available only at limited locations, on basin and global scales they are estimated. The estimation contains uncertainty, which hampers our ability to accurately quantify air-sea thermodynamic interactions and heat budgets in the tropical Atlantic (Frankignoul and Kestenare, 2005; Pinker et al., 2014; Bentamy et al., 2017). Surface turbulent fluxes are computed via bulk flux parameterizations using surface meteorological variables that can be obtained from ship reports and satellite remote sensing. Uncertainties in near-surface air temperature and humidity are the leading sources of uncertainties for satellite-derived products (Prytherch et al., 2015). This is mainly because satellites cannot retrieve the variables a few meters above the sea surface and instead rely on empirically derived algorithms applied to total-column water vapor or precipitable water (Liu et al., 1991).

The spread in net surface heat flux (Q_{net}) mean values is large across the entire tropical basin (standard deviation > 20 W m^{-2} based on 12 different products; **Figure 7**). In the tropical Atlantic away from the equatorial cold tongue, the standard deviation of Q_{net} is as large as the ensemble-mean Q_{net}. All Q_{net} products have problems achieving a balanced energy budget at the ocean surface, with an overestimation of the downward heat input to the ocean ranging from 5 to 20 W m^{-2} (Yu, 2019). For reanalysis fluxes, there are major uncertainties in tropical shortwave and longwave radiation associated with the long-standing problems of parameterizing tropical convective clouds and low-altitude stratocumulus clouds in reanalysis models (Trolliet et al., 2018). For satellite fluxes, major uncertainties are related to turbulent bulk flux parameterization schemes and also satellite retrieval algorithms. *In situ* data are crucial for anchoring global efforts to develop a global climate observing system (Weatherhead et al., 2018) and discriminate the imbalance in the Earth's radiation budget as the climate warms (Kato et al., 2013). Both reanalysis and satellite fluxes are much in need of *in situ* validation data in climatologically overcast regions such as the northeastern and particularly the southeastern tropical Atlantic (Zuidema et al., 2016b). Direct measurements of the surface heat flux have also proven valuable for diagnosing air-sea coupling in the southwestern tropical Atlantic near the Brazilian coast (Chaves and Nobre, 2004; De Almeida et al., 2007).

To make further progress on understanding and monitoring upper-ocean processes, continued measurements of ocean temperature, salinity, and velocity are needed. These observations must be capable of resolving the oceanic mixed layer and upper thermocline on diurnal to decadal timescales. Measurements of turbulent mixing and the processes that drive it, including vertical current shear, stratification, and surface buoyancy and momentum fluxes, are required both in the equatorial and off-equatorial regions. *In situ* measurements of surface fluxes

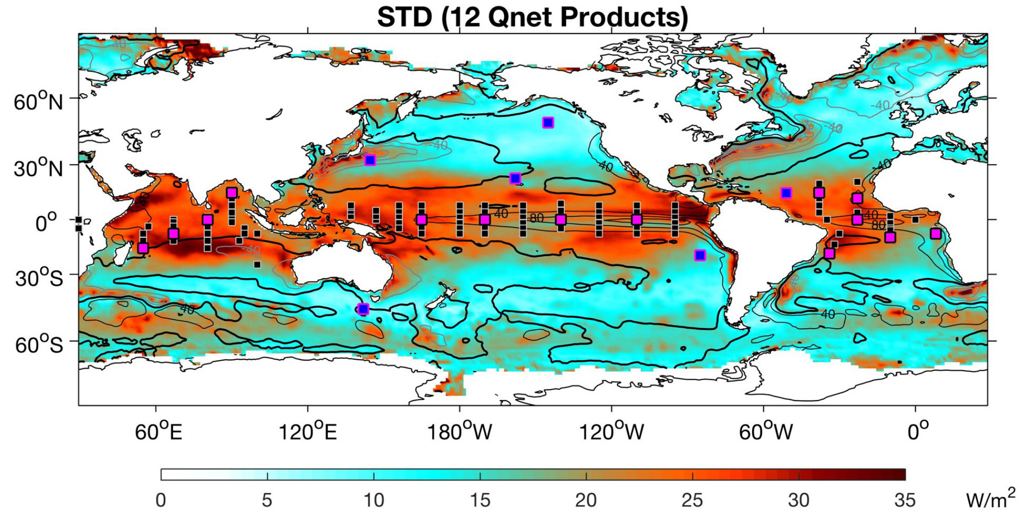

FIGURE 7 | Standard deviations between 12 mean surface heat flux (Q_{net}) products (colors) superimposed on the ensemble mean Q_{net} (contours; zero lines are highlighted). The means for all products are constructed over the same 10-year period between 2001 and 2010. Black squares denote the tropical moored arrays (PIRATA, TAO/TRITON, and RAMA) with net heat flux reference sites denoted by large magenta squares. Blue squares outlined in magenta denote OceanSITES buoys (NTAS in the tropical Atlantic). Adapted from Yu (2019).

are required throughout the tropical Atlantic and especially in cloudy regimes such as the northeastern and southeastern tropical Atlantic, and basin-scale measurements of surface parameters such as SST, surface salinity, winds, and currents are extremely valuable.

Ocean Circulation

The circulation of the tropical Atlantic Ocean is an important measure of the state of the climate system. The mean circulation sets the background conditions for the distributions of heat, salt, carbon, oxygen, nutrients, and other tracers. Due to its connection with subtropical and higher latitude regions, the tropical Atlantic circulation also affects the distributions of these quantities outside of the tropical belt. The Atlantic Meridional Overturning Circulation (AMOC) and subtropical cells (STCs) are examples of basin-wide and regional circulations, respectively, that are influenced by and interact with the circulation in the tropical Atlantic and affect tropical Atlantic climate and extreme weather (Zhang et al., 2003; Knight et al., 2005; Zhang and Delworth, 2006). At the thermocline level, the Equatorial Undercurrent (EUC) flows eastward and supplies equatorial upwelling. The strength of the EUC undergoes a strong seasonal cycle in response to wind forcing (Johns et al., 2014; Brandt et al., 2016). Interannual variability in the equatorial and eastern boundary circulation due to equatorial and coastally trapped waves define the propagation characteristics of warm and cold anomalies of the AZM and Benguela Niño (Lübbecke et al., 2010).

The eastern tropical Atlantic on both sides of the equator is occupied by OMZs, which result from sluggish ventilated shadow zones (Luyten et al., 1983) situated equatorward of the subtropical gyres. In addition to vertical mixing and lateral eddy fluxes (Fischer et al., 2013; Hahn et al., 2014), latitudinally alternating zonal jets play a dominant role in the ventilation of the Atlantic OMZs (Brandt et al., 2010, 2012). A unique feature of the eastern tropical North Atlantic is the presence of dead-zones that can develop in closed mesoscale eddy cores. Oxygen can drop to zero in these eddies (Karstensen et al., 2015), substantially lower than the average value of 40 μmol kg^{-1}. These events act to intensify the OMZ in the upper 200 m and have severe direct impacts on the local ecosystem (Schütte et al., 2016b).

At the equator, EDJs contribute to the ventilation of the eastern basin (Brandt et al., 2012). The shorter period of EDJs in the Atlantic compared to the Pacific, combined with the strong and shallow EUC in the eastern equatorial Atlantic, enables EDJs to influence interannual climate variability in the Atlantic (Brandt et al., 2011b). On intraseasonal timescales, variability in the equatorial Atlantic is dominated by TIWs in the western and central part and by wind-driven waves in the east (Athie and Marin, 2008). These waves significantly contribute to the upper-ocean heat and freshwater budgets through their influence on horizontal and vertical mixing (Foltz et al., 2003; Jochum et al., 2004; Hummels et al., 2013) and provide energy to EDJs via downward propagating Yanai beams (Tuchen et al., 2018). Moreover, there is evidence that mesoscale ocean dynamics significantly affect the tropical Atlantic Ocean and overlying atmospheric variability across a large range of time scales from daily to interannual and interdecadal (Seo et al., 2007; Chelton and Xie, 2010). Eddies are generated in the eastern side of the basin connecting the eastern boundary upwelling systems with the open oceans, transporting oxygen-poor and nutrient-rich waters into the oligotrophic ocean and impacting the mean state (Schütte et al., 2016a,b). At the western boundary, North Brazil Current (NBC) rings (**Figure 8**) and Deep Western Boundary Current (DWBC) eddies are generated

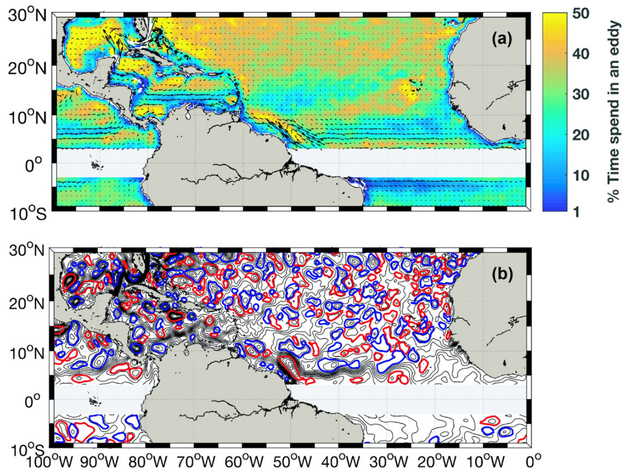

FIGURE 8 | (a) Shading shows the percentage of time each 1° × 1° box is within an eddy, based on the eddy detection algorithm of Laxenaire et al. (2019). Vectors represent the annual mean surface currents from Aviso Ssalto/Duacs and distributed by the Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu/) in the version released in April 2014 (Duacs/Aviso+, 2014; Pujol et al., 2016). **(b)** Absolute Dynamic Topography (ADT) field from Aviso Ssalto/Duacs, based on satellite altimetry on July 1, 2017, showing a well-defined North Brazil Current retroflection and North Equatorial Countercurrent in the western tropical North Atlantic. ADT is plotted every 2.5 cm. Red and blue contours indicate the maximum geostrophic velocities of anticyclonic and cyclonic eddies, respectively.

and are responsible for part of the water mass transport within the tropical AMOC (Goni and Johns, 2001; Dengler et al., 2004; Goes et al., 2009). NBC rings interact with the Amazon and Orinoco river plumes, modifying barrier layers and thus affecting TC intensification.

Major remaining questions regarding ocean circulation include (1) the role of eddies in the transport of ocean heat, salinity, and biogeochemical properties, (2) the three-dimensional structure and temporal variability of the AMOC in the tropical Atlantic, and (3) the importance of equatorial waves and the deep ocean circulation for interannual-decadal variability of the AZM. In addition, climate change will alter the tropical Atlantic circulation and its interaction with the atmosphere. Increased upper-ocean stratification, changes in wind forcing, and a changing AMOC will affect the three-dimensional transport of heat, salt, and tracers as well as regional variations in sea level, regional distributions of water mass boundaries, and shifts in ecosystems. Coupled model simulations indicate a general warming in the tropical Atlantic, with reduced seasonal cycle and interannual variability, in response to an AMOC weakening (Chang et al., 2008). Continued monitoring is needed to assess climate change impacts and validate models.

Needs for ocean circulation include basin-scale observations to measure the AMOC and the near-surface ocean circulation. The measurements must span multiple decades in order to monitor long-term changes and must be capable of resolving velocity fluctuations from mesoscale eddies and other transient phenomena, especially near the western boundary and in the equatorial waveguide.

Predictability and Model Biases

Predicting tropical Atlantic climate is challenging, and the difficulty is exacerbated by persistent coupled climate model biases. These biases have received much attention but seen little improvement (Davey et al., 2002; Richter and Xie, 2008; Richter et al., 2014b; Giarolla et al., 2015; Zuidema et al., 2016b). The tropical Atlantic biases weaken the Atlantic's global impact in models (McGregor et al., 2018). Predicting the AZM is particularly challenging, with dynamical forecasts often matched or even outperformed by persistence forecasts (Stockdale et al., 2006; Richter et al., 2017). It has been suggested that the AZM may be predictable with an anomaly correlation coefficient of 0.55 at 4 months lead (Ding et al., 2010). While most prediction models drop well below that by lead month 3 (Richter et al., 2017), some promising systems show skill in predicting the AZM in summer when initialized on May 1 (Prodhomme et al., 2016). To what extent model biases contribute to the poor skill in predicting the AZM is unclear, and very few studies have addressed this problem.

Variability of SST and other climatic variables in the northern tropical Atlantic is of great interest because most hurricanes form there. Hurricane-permitting global climate model simulations are becoming increasingly feasible (Patricola et al., 2014; Wehner et al., 2014; Walsh et al., 2015; Haarsma et al., 2016), but tend to overpredict hurricane activity if oceanic feedbacks are neglected (Zarzycki, 2016; Li and Sriver, 2018). Coupled atmosphere-ocean simulations are therefore needed for hurricane projections. However, the cool SST bias in the northern tropical Atlantic, common to coupled models (Richter, 2015; Zuidema et al., 2016b), can cause a 65% under-representation of Atlantic hurricane activity (Hsu et al., 2019). This suggests that the northern tropical Atlantic is a good target for coupled model improvement and possibly more ocean observations.

Models typically produce too weak of a cold tongue that also appears too late in the year, while placing cool SST in the western equatorial Atlantic warm pool, defined as the area with SSTs above 28.5°C. One contribution to the insufficient cold tongue development in models is the equatorial westerly wind bias in March–May (**Figure 9**), which deepens the thermocline and inhibits cooling during the subsequent June–August upwelling season (Richter and Xie, 2008; Richter et al., 2012). It may be linked to the erroneous southward shift in the Atlantic ITCZ, which is also present in atmosphere-only simulations (**Figure 9B**; Richter et al., 2014b), and the misrepresentation of convective momentum transport in the lower troposphere (Zermeño-Diaz and Zhang, 2013; Richter et al., 2014b). Tackling these problems will require detailed observations of the lower troposphere to gather observations that can guide error diagnosis and efforts toward improving convective parameterizations.

Another factor that may contribute to the cold tongue bias is insufficient representation of the oceanic thermocline (Hazeleger and Haarsma, 2005; Xu et al., 2014b), which may be related to deficiencies in vertical mixing parameterizations. Another

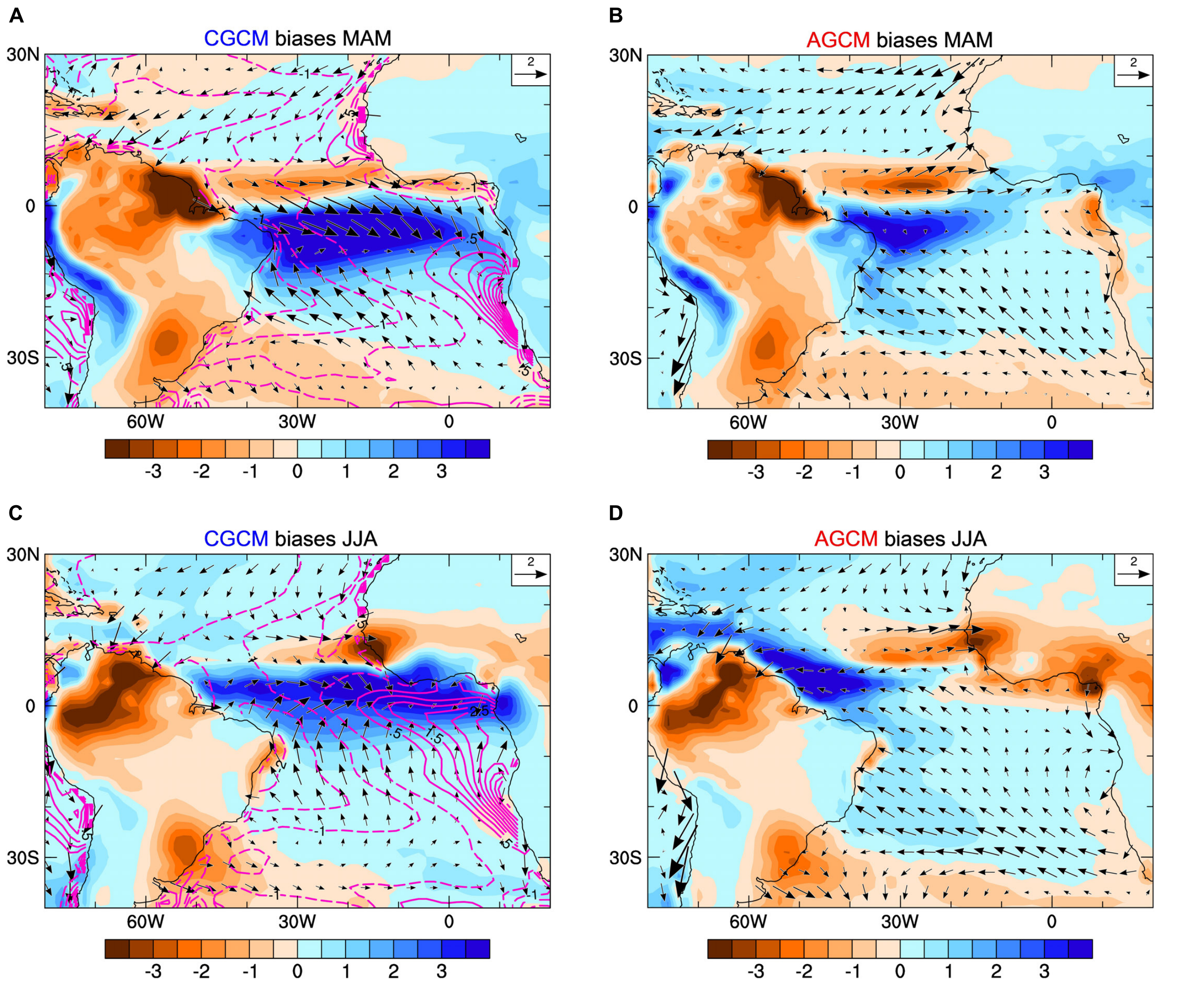

FIGURE 9 | Biases of precipitation (shading; mm day^{-1}), surface winds (vectors), and SST (contours; K) for an ensemble of CMIP5 models. Panels show the biases for **(A)** control experiment in March–April–May using coupled general circulation models (CGCM), **(B)** experiment AMIP [atmospheric general circulation models (AGCM) only] in MAM, **(C)** control experiment in June–July–August, and **(D)** experiment AMIP in JJA. The reference data sets are the Global Precipitation Climatology Project (Adler et al., 2003) for precipitation, the European Centre for Medium-Range Weather Forecasts Interim Reanalysis (Dee et al., 2011) for surface winds, and Reynolds optimally interpolated dataset (Reynolds et al., 2002) for SST.

possibility is an overly weak AMOC, which generates a cold SST bias in the North Atlantic and warm bias in the Atlantic cold tongue (section "Ocean Circulation"; Wang et al., 2014). Poor representation of the AZM in many models appears related to the under-representation of the thermocline feedback associated with an overly deep mixed layer and too weak upwelling in the eastern Atlantic (Ding et al., 2015a,b; Deppenmeier et al., 2016; Dippe et al., 2018; Jouanno et al., 2017).

The warm SST bias in the Benguela coastal upwelling region (**Figure 9**) is more severe than that at the equator, exceeding 2.5°C in the multi-model average of atmosphere-ocean general circulation models (AOGCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Toniazzo and Woolnough, 2014; Richter, 2015; Zuidema et al., 2016a). Upwelling is driven by southerly winds associated with the Benguela low-level coastal jet, with oceanic currents and the location of the Angola-Benguela frontal zone sensitive to the jet's wind-stress curl (Colberg and Reason, 2006; Fennel et al., 2012). There are two main causes of the model errors in this region: (1) equatorial biases (Rouault et al., 2007), and (2) errors in local winds, especially the Benguela Jet (Xu et al., 2014a; Koseki et al., 2018; Voldoire et al., 2019) and the Benguela Current (Grodsky et al., 2012a; Muñoz et al., 2012). Some uncertainty remains in the actual near-coastal wind-stress curl, owing to the lack of reliable satellite data and atmospheric observations near land (Desbiolles et al., 2016). Many data products poorly represent the atmospheric and oceanic circulations in the region (Large and Yeager, 2008; Patricola and Chang, 2017; Tchipalanga et al., 2018), underscoring the need for updated products at higher resolution.

Relatively little is known about the vertical structure and seasonality of the poleward Angola current (Tchipalanga et al., 2018), though data from recently deployed buoys in the region are beginning to shed some light on this (Kopte et al., 2017). Likewise, the low-level atmospheric jet along the Angola-Namibia coast is relatively poorly observed. As a consequence, even the theory underpinning the existence of the Angola current is not completely settled (Junker et al., 2015). Based on reliable SST observations, we know that the Angola current and the associated ABF are placed too far south in GCMs by about 10° of latitude (Xu et al., 2014a; Koseki et al., 2018). In the absence of reliable theoretical and observational guidance, it is difficult to alleviate this problem.

The southeastern tropical Atlantic is home to one of the largest low-latitude semi-permanent stratocumulus decks on the globe. The large-scale meteorology that affects low clouds in this region is influenced by strong coupling between the Atlantic basin and neighboring continents (Adebiyi et al., 2015; Adebiyi and Zuidema, 2016). Both the northeastern and southeastern Atlantic low clouds are affected by large dust and smoke outflows off of continental Africa. Because of the large spatial extent of the shortwave-absorbing aerosols, they are capable of influencing the interhemispheric energy balance, the location of the ITCZ, and regional precipitation patterns (Jones et al., 2009; Randles and Ramaswamy, 2010; Sakaeda et al., 2011). Positive dust and cloud feedbacks on SST and climate have been established at interannual and decadal timescales in both hemispheres (Evan et al., 2011; Bellomo et al., 2015; Myers et al., 2018) and are capable of amplifying the AMV (Bellomo et al., 2016; Yuan et al., 2016). How the corresponding smaller-scale aerosol-cloud interactions are interwoven with the individual radiative aerosol and cloud feedbacks remains a topic of research (Zuidema et al., 2016b).

One common attribution of the warm SST biases in the Southeast Atlantic is an under-representation of the marine stratocumulus deck, which then allows too much sunlight to reach the ocean surface. This introduces a positive feedback: the warmer ocean surface reduces the lower tropospheric stability that maintains the low cloud deck (Klein and Hartmann, 1993; Huang et al., 2007; Hu et al., 2008), further reducing the low cloud cover. Even when the CMIP surface radiative forcing is correct, the cloud cover is still typically too low (de Szoeke et al., 2012), likely due to an underestimation of optically thin stratiform clouds (Nam et al., 2012; Zuidema et al., 2012; Delgadillo et al., 2018; Wood et al., 2018). However, two findings complicate this interpretation. One is that the turbulent surface fluxes often overcompensate for the enhanced shortwave warming (de Szoeke et al., 2010). The other is that even for AMIP simulations in which the SST is specified, the cloud radiative effect on the surface is still underestimated, with bias reductions of only ∼25% (Zuidema et al., 2016a). This suggests the atmospheric component of the coupled models is the primary culprit (Lauer and Hamilton, 2013), with the ocean playing a vital but secondary role (Richter, 2015). Several studies have reported improved Atlantic equatorial SST, precipitation, and wind climatologies after improving their cloud radiative biases (Hu et al., 2008; Wahl et al., 2011), and efforts to improve cloud representation in models are ongoing (Bodas-Salcedo et al., 2011; Qu et al., 2014; Dal Gesso et al., 2015; Neggers, 2015; Webb et al., 2017). The cause of parameterization biases is often model specific (Medeiros et al., 2012), and ongoing observations of the boundary layer thermodynamic structure and its cloud, precipitation, and aerosol vertical structure, including the diurnal cycle, are needed for continued model improvement. Such observational datasets remain sparse for the Southeast Atlantic.

An observational network aimed at understanding and reducing model biases should include comprehensive measurements of the lower troposphere as well as surface heat and freshwater fluxes, wind stress, and ocean currents, and mixing in the equatorial and southeastern tropical Atlantic. Targeted measurements of clouds and lower tropospheric winds, temperature, and humidity in the Atlantic ITCZ region would also be beneficial.

Data Assimilation

The tropical Atlantic observing system is not designed to resolve all important spatial and temporal scales of variability. However, observations are used in data assimilative models that merge observations with ocean general circulation models forced by numerical weather prediction (NWP) fields or atmospheric reanalyses. These ocean state estimates reconstruct a dynamically consistent past evolution of the ocean, adding significant value to the existing collection of measurements. Through their inclusion in assimilative models, observations are also a valuable component of medium- to long-range prediction systems. It is therefore important that the design of the observing system takes into account the strengths, weaknesses, and future directions of analysis, reanalysis, and forecast systems.

Data from the tropical Atlantic observing system are not only used in oceanic data assimilation, but also in atmospheric analyses. From a NWP perspective, Poli (2018) analyzed the impact of observations on the ECMWF operational data assimilation scheme and showed that surface pressure measurements from PIRATA buoys have a higher positive impact per datum than many other types of observations (satellite, upper-air, land surface, or sea surface other than buoys). For instance, the impact of surface pressure is one order of magnitude larger than the impact of wind measured on the same buoys. However, satellite scatterometer, altimeter, and synthetic aperture radar data are providing valuable assimilation constraints for wind and sea-state forecasts by NWP systems (Isaksen and Janssen, 2004; Dragani et al., 2015).

Most tropical Atlantic Ocean short term prediction systems are global, eddy-permitting, and assimilate available remote sensing and *in situ* data transmitted in real-time. These systems are based on multivariate three-dimensional variational (3DVAR) and 4DVAR and ensemble approaches. They currently assimilate satellite altimetry, radiometry, and imagery to correct the surface model's sea level, temperature, and chlorophyll content. There have been some successful attempts to assimilate microwave data from the Soil Moisture and Ocean Salinity (SMOS), Aquarius, and Soil Moisture Active Passive (SMAP) satellites to correct SSS (Martin, 2016).

With the advent of coupled analysis and reanalysis systems, it is likely that the optimization of the tropical Atlantic observing system will become increasingly important. From an uncoupled ocean perspective, there is also a strong impact from water mass observations over the full water column, which have been shown to improve reanalysis fields locally by several units in temperature and salinity (Oke et al., 2015; Turpin et al., 2016; Gasparin et al., 2018). The vertical structure of currents and water mass properties at depth, especially near the thermocline, is drastically improved with the assimilation of *in situ* ocean data. For instance, Busalacchi (1996) showed that the direct assimilation of sea level and thermocline depth observations improves the upper-ocean structure in the equatorial Atlantic. The assimilation of PIRATA data was also found to improve significantly the intra-seasonal variability of upper-ocean temperature (Belyaev et al., 2001), while the impact on seasonal to longer-range prediction systems needs to be investigated and quantified in more detail. In order to guide observing system agencies and improve the use of observations in ocean models, multisystem approaches, mostly based on observing system experiments and reanalysis intercomparisons, are increasingly being used. Sophisticated (e.g., variational) quality control procedures have also shown promise for handling different observing networks in the tropical Atlantic, where, for example, large freshwater variability due to river outflow and the presence of the ITCZ may make conventional quality control methods ineffective (Storto, 2016).

At NOAA/NCEP, monthly ocean state monitoring is performed as part of a Real-Time Multiple Ocean Reanalysis Intercomparison Project (RT-ORA-IP). The intercomparison, based on nine operational systems, was motivated by the need to study the influences of the tropical Pacific observing system on uncertainties in the tropical Pacific Ocean state estimation (Xue et al., 2017). This project has been expanded to cover the tropical Atlantic and shows that overall, in the equatorial Atlantic the agreement between reanalyses is often reasonable. However, locally the spread between estimates can reach 2°C in the thermocline[7].

Sustaining and enhancing measurements is important to reduce such discrepancies among the reanalysis products. For example, the RT-ORA-IP exercise illustrates that in spite of a reasonably well captured thermocline structure along the equatorial band, heat content anomalies close to the mouth of the Amazon show strong disagreement due to large differences in river discharge applied in the different reanalyses and the associated resultant differences in local ocean circulation. Ocean prediction and reanalysis systems will greatly benefit from a sustained observing network in this area and, similarly, in the Gulf of Guinea. Most data assimilation systems also suffer from overly simplistic balance (cross-covariance) formulations close to the equator that may jeopardize the assimilation of local observations. These difficulties often result from extensions of geostrophic balance using empirical approximations (e.g., Weaver et al., 2005). Thus, data assimilation systems must evolve and account for the complex, time-varying balance in the tropics.

The skills of ecosystem models depend on physical forcing (e.g., temperature and currents) and biogeochemical variables (e.g., primary production and dissolved oxygen concentration), as well as bottom parameters for models that include coastal and shelf slopes. Whereas in ocean models' operational systems data are assimilated to correct biases, biological and fisheries data are often assimilated into models to optimize their parameters. Fish stock assessment models have developed quantitative methods to optimize the population dynamics parameters of exploited species based mainly on catch and fishing effort data, and in some cases tagging data (Maunder and Punt, 2013). Conversely, ecosystem models have rarely included such quantitative approaches. The Spatial Ecosystem and Population Dynamics Model (SEAPODYM) is an example of a modeling framework for the dynamics of phytoplankton, zooplankton, and micronekton (small but actively swimming organisms) and the detailed dynamics of key exploited fish populations (e.g., tunas, swordfish, mackerel) and their fisheries. Parameters of each model component (zooplankton, micronekton, exploited species and fisheries) are estimated using observations and data assimilation methods. A recent major development is the use of acoustic observations at multiple frequencies rather than a single one (usually 38 kHz) to reconstruct a proxy of micronekton biomass, since various species or groups of species can be distinguished by their specific responses in frequency space (Verma et al., 2017; Proud et al., 2018).

In addition to reanalysis intercomparison, Observing System Simulation Experiments (OSSEs) have been carried out recently within the Horizon 2020 AtlantOS project (2014–2019, Visbeck et al., 2015), based on a multi-system approach including both satellite and *in situ* observations. Temperature and salinity errors were reduced by 5–10% in the upper 2000 m with an enhancement of Argo sampling in equatorial regions and by around 20–30% in the deep ocean due to the implementation of deep Argo (Gasparin et al., 2019). The present tropical mooring array provides invaluable time series for evaluation of models and assimilation systems, the latter being primarily impacted in the region of the moorings. The high temporal sampling rates of moorings are not exploited in most current assimilation systems, and the mooring impact could potentially be larger with better adapted and more advanced assimilation systems. While data assimilation techniques and OSSEs are less mature for biogeochemical observations, dedicated experiments suggest that assimilation of biogeochemical Argo data will complement satellite surface color data by improving model estimates of oxygen, nutrients, carbon, and chlorophyll throughout the water column. Such dedicated activities require large time commitments and dedicated infrastructure, including running research and development versions of operational ocean analysis and forecasting systems. They also need careful planning and guidance to focus on observing system contributions at specific spatial and temporal scales and desired process-oriented metrics.

The observing system requirements for data assimilation are broad, and work is underway to quantify the specific needs. Measurements of temperature and salinity in the deep

[7] http://www.cpc.ncep.noaa.gov/products/GODAS/multiora93_body.html

ocean and surface atmospheric pressure appear to be top priorities for improving operational data assimilation and ocean state estimates. Measurements in the northwestern and southeastern tropical Atlantic are very important. Uncertainties in ocean reanalyses are largest in these regions due to sparse observations, large model errors and uncertainties in river run-off as well as air-sea heat, moisture, and momentum fluxes. Direct measurements of biogeochemical and biological parameters are needed throughout the tropical Atlantic to improve their representations in ocean and coupled models. Future coordination between modeling and data assimilation experts and observational experts is essential for proper design and interpretation of OSSEs, especially in order to extract compelling messages on the ability of the ocean observing system to resolve certain processes.

Biogeochemistry, Ecosystems, and Pollution

Interannual variability of air-sea CO_2 fluxes is closely linked to climate variability (Lefèvre et al., 2013; Ibánhez et al., 2017). Thus, improving understanding and monitoring of tropical Atlantic climate will improve knowledge and predictability of CO_2 fluxes. Carbon trends remain unclear because of the relatively short time records and high variability of the tropical Atlantic, but observations in the western tropical North Atlantic show a slower increase of seawater pCO_2 than the atmospheric growth rate from 2002 to 2009 (Park and Wanninkhof, 2012) followed by a large increase almost twice the atmospheric growth rate from 2010 to 2018 (Wanninkhof et al., in preparation), suggesting strong decadal variability.

Based on oxygen observations from repeat ship sections in the OMZ of the eastern tropical North Atlantic for the recent decade (2006–2015), Hahn et al. (2017) suggested the existence of strong oxygen variations over this decade that are superimposed on the multi-decadal deoxygenation pattern (Stramma et al., 2009; Brandt et al., 2015; Santos et al., 2016). Ocean warming and the related solubility effect are responsible for about half of the multi-decadal oxygen decline in the upper 1200 m (Schmidtko et al., 2017). Mechanisms that are responsible for the other half are unclear and are likely related to changes in ventilation and circulation (Brandt et al., 2015; Oschlies et al., 2018), though changes in biological activity cannot be ruled out. Oxygen changes in the tropical North Atlantic during the past decade are most likely associated with changes in the eddy-driven zonal current bands at intermediate depths and a shoaling of the wind-driven thermocline circulation, but other processes, such as variations in the intensity of the mesoscale eddy field, may contribute (Hahn et al., 2017).

Other main scientific questions are related to the roles of natural and anthropogenic processes that affect physical and biogeochemical changes on different timescales and their impact on marine ecosystems and biodiversity. In the context of climate change, ocean acidification is a key concern (Feely et al., 2004; de Carvalho-Borges et al., 2018). In many regions of the tropical Atlantic, the rate at which pH is declining, its causes, and its impacts on $CaCO_3$ shell-forming species are not well known. One of the longest moored pCO_2 time series in the tropical Atlantic is located at 6°S, 10°W and began in 2006. Acidification has been examined at this site, though the record is not long enough to detect any increase in CO_2 (or decrease of pH) given the strong natural variability of CO_2 (Lefevre et al., 2016). Documentation of the fate of organic matter (OM) in OMZs is also of paramount importance. Organic matter produced in the well-lit layer could be either preserved and exported, or degraded and available for marine organisms. OMZs are expected to strengthen the biological carbon pump, as surface-produced OM is better preserved due to oxygen deficiency. This assumption does not account for the intense microbial activity, which may foster OM degradation or remineralisation (Bretagnon et al., 2018). An estimation of the particle flux attenuation from satellite observations has been developed (Bretagnon, 2018) and may lead to improved predictions of oxygen inventory trends. It would also help to study the impact of oxygen variability on the remineralisation efficiency.

In the eastern tropical Atlantic, estimates of the biological pump and its dependence on oxygen availability are complicated by the presence of mesoscale eddies, which contain shallow (40–100 m) suboxic environments (Karstensen et al., 2015). In these structures the vertical distributions of particulate and dissolved OM show higher concentrations in the surface mixed layer (0–70 m). Inside the eddies' cores, oxygen consumption can be an order of magnitude higher than the average values for the North Atlantic, and the downward flux of organic matter exceeds typical values found in the open ocean (Fiedler et al., 2016). A current lack of monitoring of biological variables and their controls makes it challenging to determine how the ecosystems will cope with the changing conditions.

In models, interannual variations of temperature, nitrate, and oxygen concentrations along the southwestern coast of Africa are primarily controlled by oceanic teleconnections associated with equatorial wave variability and along-shore water mass transport (Mohrholz et al., 2008; Bachèlery, 2016; Bachèlery et al., 2016a,b; Koungue et al., 2017). Equatorially forced waves propagate along the southwestern African coast, triggering substantial thermocline, halocline, and nutricline displacements and affecting the local marine ecosystems balance, while tropical nutrient-rich and low-oxygen water masses may occasionally penetrate southward over large distances along the coast. Observations are needed to verify model results and the sensitivity of biogeochemistry and ecosystems to local and remote forcing.

For fisheries, the resource, commercially important fish stocks, needs to be assessed in terms of current stock status, including age structure and recruitment (i.e., the production of offspring). Thus, there are clear direct monitoring needs: reporting catches, including determination of age, length and weight of samples of each commercial species and the respective effort to harvest them. In addition, many countries perform fisheries independent activities such as trawl surveys, hydroacoustic surveys, and egg and larvae surveys, for independent measures of the state of a given fish stock. However, to understand the mid- to long-term development of stocks, information on the ecosystem besides the development of prey and predators is needed. This includes phytoplankton, zooplankton, micronekton, fish, shellfish, benthic organisms (corals, sponges, etc.) and megafauna (seabirds and marine mammals) on the biological side, and changes in the marine environment either through climate variability or global warming induced long-term trends (see discussion of ecosystem models and assimilation in Section "Data Assimilation"). Pollutants such as mercury and plastics can negatively impact ecosystems, and emerging contaminants such as gadolinium, silver, and platinum need close attention, as their fate, toxicity and distributions are not well known (Hatje et al., 2018; Henderson et al., 2018). Monitoring of trace-metal cycles, and novel approaches to assess their interaction with ecosystems, will be required as the ocean responds to anthropogenic stressors. A list of human activities that exert pressures on the ocean environment and have negative impacts on ecosystems can be found in **Table 1**.

The observing needs for biogeochemistry, ecosystems, and pollution include the development of long time series of key variables such as oxygen, CO_2, chlorophyll, nutrients, and commercial and endangered species, for monitoring and understanding seasonal, interannual, decadal, and longer timescale changes. These measurements are especially important in OMZs, upwelling and other near-coastal regions, and at key sites to monitor ocean acidification. Harmful pollutants such as plastics must be monitored, and internationally integrated fish stock and endangered species surveys are also a high priority.

TABLE 1 | Drivers, pressures and state variables.

Driver (human activity)	Pressure	State (change)
Fisheries	Selective extraction of species	Habitat
Coastal development	Abrasion	Foodwebs
Offshore structures	Substrate loss and smothering	(Primary) Productivity
Maritime transport	Introduction of exotic species, Direct/ indirect discharge of effluents and dumping at sea	Benthos Air, sediments and water quality; Habitat lost
Marine mineral exploitation	Selective extraction of non-living resources	Benthos Air, sediments and water quality; Biodiversity loss
Navigation dredging	Death or injury by collision	Benthos, Fish, biodiversity
Tourism and recreation	Marine litter (including plastic)	Seabirds, esthetics
Telecommunication	Pollution (noise etc.)	Marine mammals
Aggregate extraction (e.g., sand)	Eutrophication	Coastal waters, beaches
Renewable energy (algae biofuel)	Algae blooms	Coastal waters, marine biota
Land based activities (mining, agriculture, infrastructure, industries, submarine sewage outfalls, burning of fossil fuels, oil and gas exploration)	Underwater noise Emission of nutrients, trace inorganic and organic contaminants	Air, sediments and water quality; biomagnification of contaminants along the food web, compromise of food security, loss of ecosystem services.

THE EXISTING OBSERVING SYSTEM

This section summarizes the existing tropical Atlantic observing system and explores the extent to which it meets the needs of the science drivers put forth in Section "Science Drivers".

In situ Observations

Moored Buoys

The Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) serves as the backbone of the *in situ* observing system (**Figure 2**; Bourlès et al., 2008, 2019). It was initiated in 1997 and now consists of 18 moorings spanning the basin. All moorings measure ocean temperature in the upper 500 m, salinity in the upper 120 m, and near-surface air temperature, relative humidity, wind velocity, rainfall, and incident shortwave radiation. The vertical spacing of temperature sensors varies between moorings and is typically 5–20 m in the upper 40 m, with 20 m intervals down to 140 m and 40–200 m resolution between 140 and 500 m. Conductivity is additionally measured with 5–20 m spacing in the upper 40 m and 20–80 m spacing down to 120 m. Several moorings also measure downward longwave radiation, atmospheric pressure, and ocean currents at a depth of 10 m or 12 m. Daily averaged data are transmitted in real-time. A transition to the next-generation tropical flex moorings (T-Flex) began in 2015. Currently, 10 PIRATA buoys have been upgraded and the remaining eight will follow (**Figure 2**). The main advantage of T-Flex is that much larger amounts of data can be transmitted. At present, all T-Flex moorings send hourly averages in real-time.

At the equator, several subsurface acoustic Doppler current profiler (ADCP) moorings are maintained as part of PIRATA (Bourlès et al., 2019). They measure currents typically from depths of about 30 to 300 m. Several German and French projects have deployed additional deep and intermediate-depth current meters to the ADCP moorings (Brandt et al., 2006; Bunge et al., 2008). Other projects have also taken advantage of the PIRATA moorings as platforms of opportunity. Beginning in 2014, all buoys have been equipped with acoustic receivers at a depth of 200 m as a contribution to the Ocean Tracking Network (OTN[8]). The 10°W and 23°W equatorial moorings have been equipped with turbulence sensors (χpods) as part of an Oregon State University (OSU) Ocean Mixing Group program that will run for 5 years. In 2017, 10 additional point acoustic current meters were implemented at 4°N, 23°W between 7 and 87 m depths for the NOAA/AOML Tropical Atlantic Current Observations Study (TACOS) experiment, and a subset of those sensors was redeployed in 2018.

PIRATA has also supported biogeochemical measurements. Since 2006 at 6°S, 10°W and since 2008 at 8°N, 38°W, CO_2 Carbon Interface Ocean Atmosphere (CARIOCA) sensors have been measuring the fugacity of CO_2 (fCO_2) at a depth of about

[8] http://oceantrackingnetwork.org/

1 m. In 2017, a new CARIOCA sensor was implemented at 6°S, 8°E. Since 2008, the moorings at 4°N, 23°W and 12°N, 23°W have measured dissolved oxygen (O_2) at depths of 300 and 500 m in order to monitor the OMZ. O_2 sensors were recently added at 20.5°N, 23°W (Bourlès et al., 2019).

Other moorings in the tropical Atlantic include the Northwest Tropical Atlantic Station for air-sea flux measurements (NTAS) at 15°N, 51°W, the Melax air-sea buoy in the Senegalese part of the Canary Current Upwelling System at 14°N, 17°W, the Cape Verde Ocean Observatory (CVOO) at 17.6°N 24.3°W, and several meteorological and wave buoys maintained by the National Data Buoy Center (NDBC). NTAS has been operational since 2001 and measures the same parameters as the PIRATA buoys (surface meteorology including longwave radiation and atmospheric pressure), plus ocean currents from a point meter at 10 m and an upward-looking ADCP at 100 m, and enhanced vertical resolutions of temperature and salinity. The Melax buoy is on the continental shelf and measures the same parameters and oxygen at the seafloor. CVOO is part of the Cape Verde Observatory, which consists of operational atmospheric and oceanic monitoring sites for climate-relevant environmental parameters in the tropical eastern North Atlantic Ocean. Most NDBC moorings measure wind velocity, atmospheric pressure, and SST. Some buoys additionally measure significant wave height and direction and relative humidity. Data from NTAS and the NDBC moorings are transmitted in real-time, whereas only atmospheric data, SST, and surface salinity are relayed in real-time from Melax.

Argo

Argo is a global array of autonomous floats that sample the upper 2000 m of the ocean (Jayne et al., 2017). The floats drift at a depth of 1000 m and make profiles of temperature, salinity, and pressure in the upper 2000 m typically every 10 days. Measurements began in the early 2000's and there are currently approximately 4000 floats in the global ocean. About 800 floats must be deployed each year to maintain the array.

Argo is expanding its measurement capabilities to include full-depth (4000–6000 m) profiles (Zilberman and Roemmich, 2017). The deep Argo array currently consists of 69 floats, 9 of which are in the tropical Atlantic (**Figure 2B**). The project's goal is to deploy 1228 deep Argo floats globally, each with the ability to measure temperature, salinity, and pressure to within ±0.001°C, ±0.002 psu, and ± 3 dbar, respectively, improving on the standard float accuracies of temperature and salinity. Increased accuracy is required in order to resolve very small variations that can exert a large influence on global and regional mass, heat, and freshwater budgets.

The biogeochemical (BGC) Argo program was developed to improve scientific understanding and monitoring of the ocean's carbon uptake, oxygen variability, nitrate cycle, ocean acidification, the biological carbon pump, and phytoplankton communities (Gruber et al., 2010). Profiles of biogeochemical (BGC) parameters are currently made by 329 Argo floats in the global ocean, of which 22 are in the tropical Atlantic (**Figure 2B**). The measured parameters include oxygen, chlorophyll-a, suspended particles, nitrate, pH, and downwelling irradiance. Suspended particles include phytoplankton, their microscopic predators, as well as bacteria that decompose organic material. Downwelling irradiance in the ocean enables estimates of the concentrations of chlorophyll and dissolved organic matter and the amount of light available for primary production.

Repeat Hydrographic Surveys and Ships of Opportunity

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) conducts high-quality, full-depth measurements in the global ocean approximately once per decade (**Figure 10**). The measurements have high spatial and vertical resolutions and measure many different physical, chemical, and biological variables, including heat, freshwater, carbon, oxygen, nutrients and transient tracers. These measurements are used to document ocean changes throughout the water column and are especially important for monitoring the deep ocean below 2 km, which is not sampled globally by profiling floats. Different national and international programs contribute to hydrographic and velocity measurements along repeat sections near the western (5°S, 11°S) and eastern (18°N, 11°S, 23°S) boundaries (**Figure 10**).

The ship-of-opportunity program (SOOP) acquires measurements from volunteer merchant ships that regularly traverse certain shipping routes. Currently, there are three transects in the tropical Atlantic, each repeated approximately every 3 months (**Figure 10**). XBTs are deployed 10 to 35 km apart to measure temperature in the upper 760 m, from which mesoscale eddy variability and the larger-scale ocean circulation can be deduced (Goes et al., 2013). Thermosalinographs (TSGs), instruments mounted close to the water intake of ships to continuously measure SSS and SST, record measurements along two SOOP transects. Surface ocean CO_2 fugacity (fCO_2), temperature, and salinity are also measured on some voluntary observing ships. The number of measurements of fCO_2 increased from about 0.3 million per year during 1995–2000 to 1.1 million per year during 2005–2012 (Bakker et al., 2016).

Annual PIRATA servicing cruises provide opportunities for repeated shipboard measurements. These consist primarily of conductivity-temperature-depth (CTD) casts, often with measurements of O_2 and currents from lowered ADCPs (**Figure 10**). PIRATA cruises also allow for deployments of Argo floats, surface drifters, radiosondes, and ozonesondes, and for water sample analysis to determine concentrations of O_2, CO_2, and chlorophyll. In 2017 and 2018, full-depth CTD-O_2-ADCP casts, along with water sample analyses of salinity, O_2, pH, nutrients, and trace elements, were performed during the western Atlantic PIRATA servicing cruises. Flux tower measurements of momentum, humidity, and CO_2 at the ocean-atmosphere interface were also made at times. Multi-frequency transects collected during the regular maintenance cruises of the PIRATA network since 2015 are a key piece of a growing acoustic network for estimating the global biomass of micronekton, one of the less known components of the ocean ecosystem.

Surface Drifting Buoys

Global Drifter Program (GDP) observations from buoys drogued at 15 m were first collected in the tropical Atlantic in 1990, and the array was sustained beginning in 1997 (**Figure 2**). Since

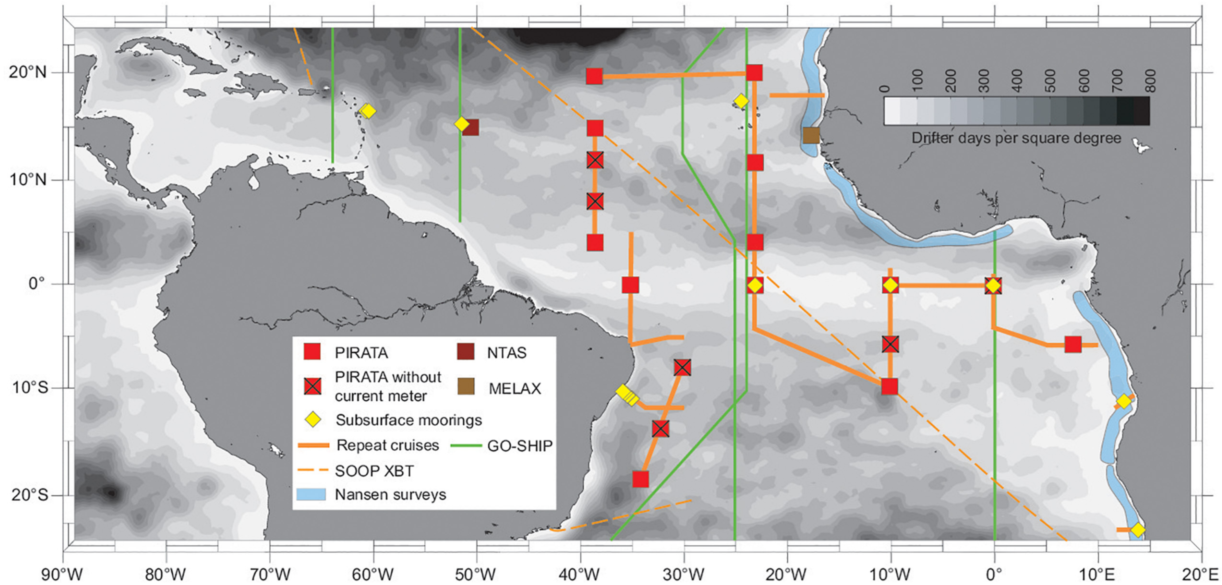

FIGURE 10 | The tropical Atlantic observing system as implemented for the study of ocean circulation and upwelling. Shading indicates total number of days any surface drifter was in each 1° × 1° box through February 2018. Surface drifter measurements in the tropical Atlantic began in 1997. Solid orange lines show repeat cruise tracks, mainly for servicing moorings, dashed orange lines show XBT lines, blue shading indicate regions where Nansen surveys (near-coastal physical, chemical, and biological sampling from a research vessel) have been conducted, and green lines show full-depth repeat hydrography cruise tracks (GO-SHIP). The brown square shows the location of the coastal air-sea buoy Melax, yellow diamonds indicate where subsurface velocity and hydrographic moorings have been deployed, and other symbols are as in **Figure 6**.

1998, the array in the tropical Atlantic has averaged 92 drifters, and since 2005 drifter measurements have been approximately hourly. Most deployments are conducted from the expendable bathythermograph (XBT) line AX8, which runs from Cape Town to the U.S. east coast, from research vessels servicing PIRATA, and from Brazilian Navy vessels. Sustaining drifter observations in the tropical Atlantic is difficult as it is a region of net surface divergence.

In addition to the standard drifter measurements of SST, surface currents, and barometric pressure, drifters have also been developed to measure subsurface temperature, surface and subsurface salinity, wind velocity, and directional wave spectra. However, few of these observations are being collected by drifters in the tropical Atlantic. Surface velocity estimates can also be calculated from Argo float trajectories while they are transmitting their data at the surface (Lebedev et al., 2007). As Argo transitions to Iridium data transmission, the floats will spend less time at the surface and thus be more strongly affected by high-frequency motion than was the case with floats using Service Argos. It is unclear how useful such measurements will be.

Boundary Current Arrays

An array consisting of four velocity moorings has been installed at the Brazilian continental slope along 11°S from 2000 to 2004 and since 2013, measuring the shallow and DWBC (Schott et al., 2005; Hummels et al., 2015). A single mooring was also deployed to observe the Angola Current. The mooring consists of an ADCP covering the upper 500 m at 11°S, 13°E and has been recording data since 2013, showing a weak and highly variable southward flow of the Angola Current (Kopte et al., 2018). In addition to the boundary current arrays at 11°S, pressure-equipped inverted echo sounders have been deployed at 300 and 500 m on the continental margins on each side of the basin since 2013 to enable comprehensive AMOC estimates at this latitude. Since 2000, a mooring array has been maintained at 16°N that includes velocity measurements covering the DWBC east of Guadeloupe and additional geostrophic moorings measuring the deep flow between the continental slope and the mid-Atlantic ridge (Send et al., 2011; Frajka-Williams et al., 2018). The 16°N and 11°S arrays contribute to the AMOC observing system and can be used to investigate links between the subtropical North Atlantic array at 26.5°N (RAPID/MOCHA/WBTS) and the South Atlantic array at 34.5°S (SAMBA). **Figure 10** shows the locations of the boundary current arrays.

Satellite Observations

Most satellites provide measurements in real-time or near real-time, and the records for many parameters extend back at least 20 years. SST is obtained from passive infrared and microwave radiometers. By combining data from several satellites with *in situ* measurements, daily maps of SST at high spatial resolution (0.25° or better) are possible going back to 1997, when microwave measurements started. Estimates of tropical rainfall and precipitable water are also available from microwave sensors. Satellite-based measurements of SSS began in 2009 with the launch of the SMOS sensor. SSS was measured by Aquarius during 2011–2015 and is currently measured by the SMAP radiometer. From these satellites, complete coverage of the tropical Atlantic is achieved in approximately one week at a spatial resolution of 1/2°–1°. Real-time blended SSS products show promise for monitoring conditions in the tropical Atlantic (Xie et al., 2014). Measurements of surface chlorophyll-a concentration, clouds, atmospheric temperature and moisture profiles, and aerosol optical depth are made routinely using infrared sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS). Complete coverage of the tropical Atlantic is achieved in approximately 2–8 days. The geostationary MeteoSat satellite provides full disk coverage at half-hourly resolution, though retrieval products are more limited. Several satellites are equipped with radar altimeters that measure sea surface height, from which the sea level anomaly with respect to the geoid can be calculated. Full coverage of the tropical Atlantic is achieved in less than 3 days.

Satellite observations have greatly improved the coverage, resolution, and accuracy of surface buoyancy and momentum flux estimates (Yu, 2018). Turbulent heat, moisture, and momentum fluxes are computed from bulk flux algorithms (Fairall et al., 2003) using surface wind speed and direction, SST, near-surface air temperature, and humidity as input. Wind speed and direction have been provided by scatterometers on a series of satellite missions. These include the European Remote sensing Satellite (ERS)-1 (1992–1996) and ERS-2 (1995–2000), the NASA SeaWinds-1 scatterometer on the QuikSCAT satellite (1999–2009), the European Space Agency's (ESA's) series of three Advanced Scatterometers (ASCAT) onboard the MetOp satellites (2006 onward), and OceanSat-2 (OSCAT; 2009–2014) and SCATSAT-1 (2016 onward) by the Indian Space Research Organization. Scatterometers measure the effects of centimeter-scale roughness caused by surface stress, but the present retrieval algorithms generate estimates of surface wind, not wind stress, because there are no suitable surface wind stress ground-truths for calibration. Instead, wind retrievals are calibrated to the equivalent neutral-stability wind 10 m above the local-mean sea surface (Liu and Tang, 1996). The 10-m equivalent neutral wind speed differs from the 10-m wind speed measured by anemometers. These differences are a function of atmospheric stratification and are normally on the order of 0.2 m s^{-1}. The differences may also reflect differences in observing platforms. For example, *in situ* wind measurements are relative to a fixed-earth reference, while satellite winds are relative to surface currents. For winds less than about 3 m s^{-1} or greater than 20 m s^{-1}, the uncertainties are generally larger. Low-wind retrievals are often problematic because the weak backscatter signal is confounded by noise, and the empirical scatterometer algorithms are not sufficiently calibrated at high winds due to the lack of *in situ* measurements.

The remote sensing of SST uses space-borne infrared and microwave radiometers to detect thermally emitted radiation from the ocean surface. Infrared radiometers such as the five-channel Advanced Very High Resolution Radiometer (AVHRR) use wavelength bands that have high transmissivity in the cloud-free atmosphere. However, clouds are opaque to infrared radiation and can effectively mask the radiation emitted from the ocean's surface. Because of the cloud effect, it takes one or two weeks to obtain a complete global SST field from AVHRR even though the satellite orbits the Earth 14 times each day and has a 2399-km-wide swath. In contrast, clouds have little effect on microwave radiometers so that microwave SST retrievals can be made under all rain-free weather conditions. The TRMM microwave imager (TMI) was launched in 1997 and was the first satellite sensor capable of accurately measuring SST through clouds. The low-inclination equatorial orbit, however, limits TMI's coverage to the 38°S–38°N latitude band. Global through-cloud measurements of SST were made possible by the Advanced Microwave Scanning Radiometer (AMSR) onboard NASA's EOS Aqua spacecraft (AMSR-E, 2002–2011) and the AMSR-2 onboard the Japan Aerospace Exploration Agency's (JAXA's) Global Change Observation Mission – Water (GCOM-W1) spacecraft (2012 onward).

Near-surface air humidity and temperature cannot be retrieved directly by satellites. Instead, these variables are estimated from satellite-measured total column water vapor or total precipitable water (PW) (Liu, 1986; Liu et al., 1991) using passive microwave radiometers such as Special Sensor Microwave Imager and Sounder (SSM/I and SSMIS, respectively), AMSR-E, and AMSR-2. The launch of the Advanced Microwave Sounding Unit (AMSU) on the NOAA series of polar orbiting meteorological satellites in May 1998 provided profiles of temperature and humidity that have been used to improve estimates of near-surface humidity and temperature (Jackson et al., 2006). Despite significant progress, these variables remain the leading source of error in satellite-based surface heat flux products.

Satellites measure downwelling and upwelling solar radiation and upwelling longwave radiation at the top of the atmosphere (TOA). The radiation budget at the ocean's surface is not remotely sensed. Instead it is estimated from radiative transfer calculations that use satellite-derived TOA irradiance, cloud and aerosol properties, and the atmospheric state from either satellites or reanalysis. Surface radiation budget estimates are produced by the Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) radiative transfer model (Kato et al., 2013). The CERES experiment was developed to measure TOA radiative fluxes and to determine radiative fluxes within the atmosphere and at the surface. CERES instruments were launched aboard the Tropical Rainfall Measuring Mission (TRMM) in November 1997, on the EOS Terra satellite in December 1999, and on the EOS Aqua spacecraft in 2002.

Precipitation at the ocean's surface is retrieved from variables that are highly correlated with rainfall, including infrared and microwave brightness temperature, as well as visible and near-infrared albedo. Infrared techniques are based on the premise that surface rainfall is related to cloud-top properties observed from space, while microwave techniques relate rainfall to microwave emission from rain drops and scattering from ice. Microwave observations are available from SSM/I, AMSU-B, and the TRMM spacecrafts. TRMM is equipped with the first spaceborne precipitation radar (PR) along with a microwave radiometer (TMI) and a visible/infrared radiometer (VIRS), thus allowing the estimation of rain profiles in addition to surface precipitation. Information from all three sensors is optimally merged to produce a three-hour precipitation field at 0.25° spatial resolution over the tropics and subtropics. The Global Precipitation Measurement (GPM) mission launched in February 2014 and carries a dual-frequency precipitation radar and microwave imager, which is able to sense total precipitation within all cloud layers. GPM extends the capabilities of TRMM sensors, including sensing light rain, and for the first time, is able to quantify microphysical properties of precipitation particles.

Strengths and Weaknesses of the Current Observing System

There is a high degree of integration among the various sustained observing components so that weaknesses of some are compensated by the strengths of others. Satellites give global coverage but only at the surface of the ocean and generally do not resolve timescales less than one day. In contrast, Argo provides subsurface information, but at coarser horizontal resolution than satellites. Moored surface buoys have even coarser horizontal and vertical resolutions than Argo, but uniquely make co-located high-temporal-resolution measurements of the upper ocean and near-surface atmosphere. *In situ* data are critical for validating and calibrating satellite retrievals, and satellite data are useful for filling temporal gaps in mooring surface data and for providing information to fill the large spatial gaps between moorings and other *in situ* surface measurements. There is therefore a high degree of complementarity between satellite and *in situ* measurements. To measure ocean circulation, surface drifters have basin-wide coverage, complementing sparse moored measurements from single-point and profiling current meters. Measurements from XBTs are able to resolve the vertical structures of eddies and give estimates of large-scale ocean transport as quasi-synoptic snapshots, while transport arrays provide estimates of AMOC components including the deep ocean or full-depth mass, heat, and salinity transports at key locations. The existing integration can be seen as a strength of the present observing system. The remainder of this section focuses on gaps in the observing system in the context of the different science drivers presented in Section "Science Drivers".

In the tropical North Atlantic, PIRATA moorings are located in the central and eastern basin (east of 40°W), where seasonal and interannual SST signals are largest, especially those associated with the AMM and AZM. However, PIRATA moorings do not sample the warm pool region to the west, where there are strong mesoscale eddies (**Figure 8**), seasonal variations of upper-ocean salinity stratification that affect SST and TCs, and strong multidecadal variations of upper-ocean heat content and SST (**Figure 11**). Moorings also do not resolve well the equatorial waveguide, especially meridionally, or the southeastern tropical Atlantic, where there are large SST signals associated with Benguela Niños, model biases, and complex ocean-atmosphere interactions involving winds, currents, SST, clouds, and aerosols. In these regions, enhanced mooring coverage may be part of the solution, but other measurements will also be needed. An effective multiplatform approach might include (1) denser sampling from Argo floats where more information on the large-scale subsurface ocean is most needed, such as the equatorial and northwestern tropical Atlantic, (2) additional moorings at key locations where upper-ocean processes and air-sea fluxes are poorly understood, such as downstream from the Amazon-Orinoco low-salinity plume and in the southeastern Atlantic stratus deck region, and (3) ocean gliders and satellite measurements of surface currents that can most effectively sample fronts and eddies.

Improvements must be made to the observing system to advance monitoring and understanding of the processes that affect SST and surface salinity. Moorings remain a key source of co-located upper ocean and air-sea flux measurements that are extremely useful for this purpose. However, the vertical resolutions of temperature sensors on PIRATA moorings are not high enough to resolve the vertical structure of the mixed layer diurnal cycle, which can affect the mean state climate and vertical mixing (Ham et al., 2009; Hummels et al., 2013). The vertical spacing of conductivity sensors on most moorings is much too coarse for accurate resolution of the mixed layer and salinity stratification required for heat and salinity budget analyses. Vertical turbulent mixing plays an important role in the equatorial mixed layer heat and salinity budgets, and this has motivated multi-year measurements of mixing at some PIRATA locations. There are strong indications that mixing is also important at off-equatorial locations and that the driving processes are very different than those operating at the equator. However, no long-term measurements of horizontal velocity, vertical shear, and turbulent mixing exist in the tropical Atlantic outside the equatorial band (**Figure 6**). Vertical velocity in the upper ocean provides important preconditioning for turbulent mixing through its impact on stratification, yet direct measurements of this quantity are lacking. There are very few measurements of surface wave height and spectra in the tropical Atlantic, which are needed to improve forecasts and to advance understanding of wave-induced upper-ocean mixing. There are large uncertainties in surface turbulent heat fluxes derived from satellite and reanalysis data (**Figure 7**), and it is unclear how well existing bulk formulas perform, especially outside of the equatorial region. It is difficult to close the heat and salinity budgets at many PIRATA mooring locations because at present less than half of the moorings have direct measurements of longwave radiation and ocean currents.

A more complete observing system for the upper ocean will likely include measurements from many different platforms, in addition to addressing the gaps in mooring observations described above. Emerging technologies are showing promise for obtaining surface flux and upper-ocean measurements from autonomous moving platforms (Voosen, 2018). Gliders have already proven valuable for measuring upper-ocean turbulence and the factors that control it (St. Laurent and Merrifield, 2017). Satellite-based retrievals of surface radiative and turbulent fluxes show considerable skill (Yu and Weller, 2007; Trolliet et al., 2018) and are likely to improve further if satellite and *in situ* measurements are maintained.

Much of the present observing system was designed before coupled model biases emerged as a scientific research priority. As a result, efforts to alleviate model biases are hampered by inadequate *in situ* measurements (Tchipalanga et al., 2018).

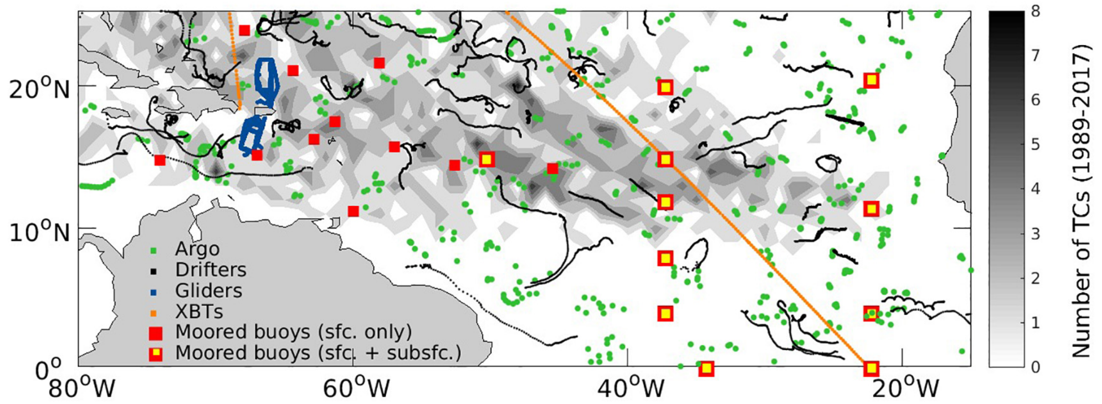

FIGURE 11 | Key components of the sustained ocean observing system for extreme weather. Shading shows the number of tropical cyclones that passed through each 1° × 1° box during 1989–2017, based on "best track" data. Black lines show the trajectories of all surface drifters during August 2018. Green dots show all Argo profiles made during August 2018. Orange lines indicate XBT lines, which are repeated approximately every 3 months, and blue lines represent ocean glider tracks during 2014–2018. Red squares indicate moored buoys with surface measurements, and yellow squares show moorings that additionally measure subsurface temperature, salinity, and/or velocity.

A more comprehensive and multifaceted observational approach is needed to make progress on this difficult problem. Based on the leading theories of what generates coupled model biases, such an improved system may include (1) arrays of near-coastal buoys and ocean gliders in the Benguela upwelling region, (2) multiplatform measurements of turbulent mixing and the processes that drive it in the equatorial Atlantic, (3) direct measurements of turbulent and radiative air-sea fluxes in the northeastern and southeastern tropical Atlantic from autonomous vehicles and moored buoys, (4) enhanced measurements of the lower troposphere in the Atlantic ITCZ region, possibly as part of a process study.

In general, biogeochemical quantities are severely undersampled compared to many physical parameters, especially in the tropical South Atlantic (**Figure 12**). Oxygen and fCO_2 are not monitored by many elements of the tropical Atlantic observing system. Due to the importance of the OMZ for marine habitat compression and air-sea CO_2 flux for the tracking of the ocean CO_2 sink, measurements of oxygen and fCO_2 co-located with physical variables should become the norm. Expanded measurements of other biogeochemical parameters, such as nutrients, pH, and ocean color, are also needed to monitor biogeochemical cycles and acidification. These may be achieved through (1) the continuation and expansion of biogeochemical Argo and *in situ* measurements from research vessels, (2) the addition of biogeochemical sensors to existing moorings, and (3) development of new technologies to measure biogeochemical parameters from autonomous and remotely controlled vehicles. Some PIRATA cruises have only recently begun to measure biogeochemical and biological parameters such as nutrients, pH/alkalinity, and phytoplankton, while others measure only temperature, salinity, and oxygen. Traditional zooplankton sampling with nets requires extra ship time, complicating its implementation. Possible alternatives include emerging technologies such as the underwater vision profiler (UVP) that can be lowered to 6000 m on a CTD rosette. In addition to taking pictures of larger particles or organisms that would normally be sampled using nets, it also captures fragile zooplankton and phytoplankton species normally not recorded in net samples (Biard et al., 2016) and has been deployed in the tropical Atlantic (Kiko et al., 2017). Alternatively, acoustic sampling of zooplankton and fish can be performed from autonomous vehicles or gliders (Lembke et al., 2018). Thus, for PIRATA the ocean biogeochemistry and ecosystem observation capabilities have not yet been fully explored.

A current lack of monitoring of biological variables also makes it challenging to determine how ecosystems will cope with changing physical and biogeochemical conditions. Many of the methods to improve biogeochemical sampling also apply to biological sampling. Complicating biological measurements is the need for a multidisciplinary approach that includes observations of physical, biogeochemical, and biological parameters. Integration of biogeochemical and biological measurements into PIRATA and Argo may be one way forward, and PIRATA and Argo would also benefit from greater international governance of biogeochemical and biological observations. Currently, there is no long-term commitment to fund these observations continuously, only to define what constitutes biogeochemical measurements and what should be measured. In addition, the biological sampling network would greatly benefit from improved international coordination and capacity building. Currently, satellite retrievals of chlorophyll and ocean color are limited by clouds, especially in the ITCZ, providing additional motivation for *in situ* measurements this region.

For ocean state estimates, the PIRATA array is too sparse and the measurements are too shallow to provide constraints on the deeper ocean. Deeper measurements, including a more complete AMOC monitoring system, are needed to constrain simulations of the AMOC, sea level rise, heat and freshwater storage, and the global energy imbalance. Currently, the deep ocean (>2000 m) is very poorly sampled, severely limiting the

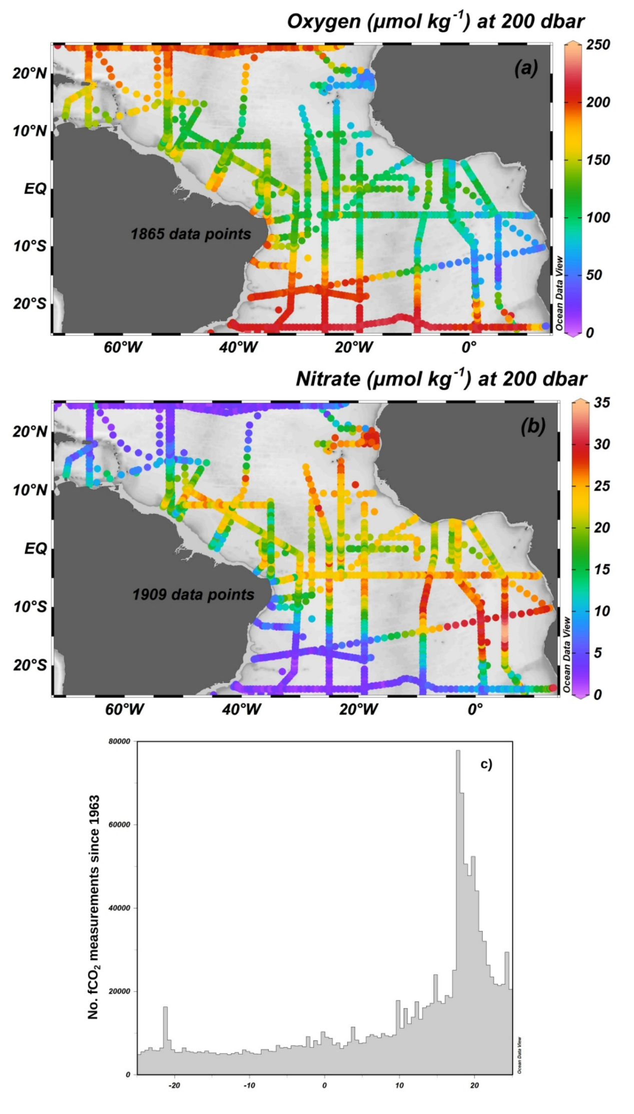

FIGURE 12 | Number of historical *in situ* measurements of **(a)** oxygen and **(b)** nitrate at 200 dbar acquired during repeat hydrographic cruises (GLODAP v2 data product, Olsen et al., 2016). Note that the color scales are different in panels **(a,b)**. **(c)** Total number of surface CO_2 fugacity (fCO_2) measurements since 1963 across all longitudes in the tropical Atlantic for each 0.5° latitude bin (SOCATv6, Bakker et al., 2016).

accuracy with which these quantities can be calculated. Global arrays such as Argo, and especially the developing deep Argo program, are likely to be most useful for this purpose. Direct measurements of the AMOC from *in situ* monitoring arrays are also needed for validation of ocean state estimates. More comprehensive design, analysis, and intercomparison of OSSEs should be explored in order to quantify the number, type, and spatial locations of additional measurements that would most likely improve ocean data assimilation and state estimates.

The tropical Atlantic observing system generates large quantities of data covering a wide range of temporal and spatial scales and across many platforms. A key challenge is to ensure consistent data processing, archiving, availability, and visibility within and across all datasets. This is important not only to increase the usability of the data for advancement of scientific knowledge, but also to improve data assimilation and predictability of weather, climate, and ecosystems. A consistent data record is also needed to evaluate the performance of the observing system over time and recommend changes to it. The archiving and availability of data has progressed over the past decade because of several developments: (1) the use of digital object identifiers (DOIs) for datasets has expanded, (2) scientific journals have started requiring statements of data accessibility, (3) funding agencies require data management and archiving plans, and (4) common data formats such as NetCDF have gained wider acceptance. However, many important datasets remain difficult to find or are stored in formats that are difficult to read or do not contain adequate metadata. A push for open data availability and visibility and consistent archiving is needed and may be achieved through a combination of approaches, including continuation of those listed above.

RECOMMENDATIONS FOR THE FUTURE OBSERVING SYSTEM

Based on the science drivers and gaps in the observing system identified in Sections "Science Drivers" and "Strengths and Weaknesses of the Current Observing System", below is a list of key recommendations for the future tropical Atlantic observing system. The recommendations include readiness levels (RL) to indicate the ease with which they could be implemented: (1) No additional action needed other than sustained funding, (2) Implementation in progress, (3) Additional funding required for implementation, (4) Scientific guidance/design and funding required. See also Bourlès et al. (2019) for a discussion of recommendations specifically for PIRATA.

- **Most importantly, maintain observing systems that have proven their long-term value for scientific research, monitoring, and operational forecasts and analyses.** These long records in the tropical Atlantic are extremely important for observing ocean-atmosphere variability on interannual to multidecadal timescales and changes in response to global warming. Continuity of satellite records is critical for maintaining basin-wide surface observations. *In situ* data provide information on the subsurface ocean and high-accuracy measurements near the air-sea interface that can be used to calibrate and validate satellite measurements and to bridge gaps between satellite missions. **RL1**
- **Improve the vertical sampling on PIRATA moorings in the mixed layer and immediately below; add new sensors for ocean velocity and surface fluxes; develop new satellite measuring capabilities.** Presently, the sensor spacing is too coarse to accurately calculate mixed layer depth, stratification beneath the mixed layer, and the vertical structure of the diurnal cycle of temperature near

the surface. It is also recommended that every mooring have at least one single-point current meter and a downwelling longwave radiation sensor. These measurements are needed to compute temperature and salinity advection and the net surface heat flux, important components of the mixed layer heat and salinity budgets. Augmenting moorings with barometers will aid NWP and data assimilation. Proposed satellite missions such as the Sea surface KInematics Multiscale monitoring of ocean surface currents (SKIM) have great potential to aid research, data assimilation, and forecasts. Their development should be continued. **RL3,4**

- **Sustained measurements of upper-ocean mixing are needed, along with the processes that drive it, such as current shear and surface waves.** This could be achieved through moored microstructure, ocean velocity, and surface wave measurements at one or two PIRATA locations on the equator and one or two locations off the equator, together with targeted deployments of autonomous vehicles and gliders. **RL4**
- **Monitoring of deep ocean temperature and salinity must be continued and expanded.** These measurements, mainly from deep Argo and some moorings, are critical for assessing long-term changes in the ocean's heat storage and mass balance, and the earth's energy imbalance. They also help to monitor and understand the AMOC. **RL2**
- **Sampling of biogeochemical and biological parameters from floats, research vessels, ships of opportunity, and moorings must be continued and expanded, especially in the tropical South Atlantic.** These measurements are required for monitoring and understanding the carbon cycle and OMZ dynamics. They must be acquired concurrently with physical parameters such as temperature, salinity, and ocean velocity. **RL2,3**
- **The moored observing system should be extended to the northwestern tropical Atlantic warm pool (AWP) and southeastern tropical Atlantic (STA), and the use of other *in situ* platforms should be expanded.** The AWP is a region through which a high percentage of land-falling hurricanes pass. There is strong upper-ocean salinity stratification and energetic mesoscale fronts and eddies that affect air-sea fluxes and mixing and yet are poorly understood. The combination of moorings that include subsurface ocean measurements, and other platforms such as gliders and Argo, would advance knowledge and predictability of landfalling hurricanes. Augmenting the *in situ* observing system in the STA will help to improve understanding of the AZM, Benguela Niños, and coupled model biases. This could be achieved through a denser network of Argo floats and PIRATA moorings near the equator and additional PIRATA moorings in the southeastern tropical Atlantic. Routine servicing cruises to new moorings should be used to measure the diurnal cycle of the cloudy boundary layer. **RL4**
- **More widespread use of autonomous platforms and gliders is recommended, especially in western and eastern boundary regions and on the continental shelf, where satellite data is unavailable or uncertain and subsurface data are sparse.** Augmenting autonomous platforms and surface drifters with additional meteorological measurements, such as atmospheric pressure, winds, air temperature, and relative humidity, would be very beneficial for improving weather forecasts and air-sea flux calculations. **RL2,3**
- **Extensions of oceanographic surveys for commercial and endangered species are needed.** In many cases this will require additional capacity-building in African nations. Another related requirement is the integration of individual surveys into a larger observational system that considers the requirements of different user groups, including society, the private sector, and the scientific community. The value of all ocean observations must be communicated more widely and clearly to society. **RL3,4**
- **The measurements of micronekton collected during the regular maintenance cruises of the PIRATA network are one on the less known components of the ocean ecosystem. These measurements must be continued and expanded to other platforms when feasible.** Routine measurements of plastics during repeated PIRATA services cruises are also highly recommended, given their detrimental impacts on ecosystems. **RL2,3**
- **Though not part of the sustained observing system, process studies are essential to improve model parameterizations, identify new scientific phenomena, and develop and test new technologies.** Process studies often measure many variables at high resolution for a limited amount of time. The information gained can inform scaled-back versions for integration into the sustained observing system and point to ways in which the tropical Atlantic observing system can be adapted for the future. **RL4**

PIRATA and other fixed moorings are unique among the observing systems because they can be placed at predefined locations and do not drift. Following the first recommendation in the list above, there are compelling reasons to sustain the current configuration of moorings. PIRATA resolves the fast zonal propagation of oceanic signals along the equator, while at off-equatorial locations they provide essential measurements across a wide range of climate regimes. These include the low-wind, high-rainfall ITCZ; the northeastern and southeastern areas with cool SSTs, low clouds, and large concentrations of aerosols; and the northwestern tropical Atlantic, characterized by strong upper-ocean salinity stratification, energetic mesoscale variability, and poorly understood shallow convection in the atmosphere. Furthermore, there are large disparities between off-equatorial winds measured directly by PIRATA and estimated by satellites and model-based reanalyses (Bentamy and Fillon, 2012), emphasizing the importance of maintaining the long records from all PIRATA moorings. Coupled ocean-atmosphere data assimilation, a promising approach to improve oceanic and atmospheric analyses and coupled model forecasts, is in its infancy (Zhang et al., 2007; Lu et al., 2015). The most valuable data for evaluating and improving the methodologies are co-located time series of oceanic and atmospheric data from fixed-point moorings. For forecast improvements, both a long history (with a record of many past events to evaluate forecast skill) and reliable real-time data (to initialize forecasts) are critical.

CONCLUSION

The tropical Atlantic represents a unique and complex mix of many interacting oceanic and climate modes of variability that fluctuate across a wide variety of timescales. A large and diverse group of human populations depends on the tropical Atlantic Ocean for sustenance and recreation and is adversely affected by climate-driven changes in precipitation patterns, extreme weather and ocean ecosystems. Therefore, the demand for information about the tropical Atlantic Ocean, including subseasonal to seasonal predictions and longer-term projections in a changing climate, is only expected to increase in the future.

There has been substantial progress in building and maintaining the sustained observing system over the past 20 years. We must continue to maintain the valuable elements of the observing system, building on the successful history of international and multidisciplinary cooperation. Critical gaps in the observing system need to be filled. This may be accomplished in part through enhancements to autonomous observing networks and investments in new technologies. The tropical Atlantic is strongly influenced by conditions in the Pacific and Indian Oceans as well as the extratropical North and South Atlantic. Therefore, the success of the tropical Atlantic observing system depends in part on the maintenance and evolution of those observing systems. Continued international cooperation and observing system integration are essential in order to maintain and improve monitoring, prediction, and scientific understanding of the tropical Atlantic Ocean and related changes in weather, climate, and ecosystems.

AUTHOR CONTRIBUTIONS

BR-F, RR, PB, MDe, IR, NL, LY, JOS, and FH led the writing of individual sections of the manuscript. GF combined all sections and wrote the full manuscript. All authors contributed to writing the sections and/or revising the full manuscript.

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The Global High Frequency Radar Network

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Academic, government, and private organizations from around the globe have established High Frequency radar (hereinafter, HFR) networks at regional or national levels. Partnerships have been established to coordinate and collaborate on a single global HFR network (http://global-hfradar.org/). These partnerships were established in 2012 as part of the Group on Earth Observations (GEO) to promote HFR technology and increase data sharing among operators and users. The main product of HFR networks are continuous maps of ocean surface currents within 200 km of the coast at high spatial (1–6 km) and temporal resolution (hourly or higher). Cutting-edge remote sensing technologies are becoming a standard component for ocean observing systems, contributing to the paradigm shift toward ocean monitoring. In 2017 the Global HFR Network was recognized by the Joint Technical WMO-IOC Commission for Oceanography and Marine Meteorology (JCOMM) as an observing network of the Global Ocean Observing System (GOOS). In this paper we will discuss the development of the network as well as establishing goals for the future. The U.S. High Frequency Radar Network (HFRNet) has been in operation for over 13 years, with radar data being ingested from 31 organizations including measurements from Canada and Mexico. HFRNet currently holds a collection from over 150 radar installations totaling millions of records of surface ocean velocity measurements. During the past 10 years in Europe, HFR networks have been showing steady growth with over 60 stations currently deployed and many in the planning stage. In Asia and Oceania countries, more than 110 radar stations are in operation. HFR technology can be found in a wide range of applications: for marine safety, oil spill response, tsunami warning, pollution assessment, coastal zone management, tracking environmental change, numerical model simulation of 3-dimensional circulation, and research to generate new understanding of coastal ocean dynamics, depending mainly on each country's coastal sea characteristics. These radar networks are examples of national inter-agency and inter-institutional partnerships for improving oceanographic research and operations. As global partnerships grow, these collaborations and improved data sharing enhance our ability to respond to regional, national, and global environmental and management issues.

Keywords: remote sensing, high frequency radar, ocean currents, waves, tsunami, boundary currents, ocean observing system

INTRODUCTION

Ocean currents regulate the climate by carrying warm water from the equator toward the poles. The ability to measure these currents will allow us to monitor and hopefully predict the trajectory of our climate. Western boundary currents are important areas for understanding and measuring the oceans impact on and response from climate processes (Send et al., 2009). Approximately 1.2 billion people (23% of the world population) live within 150 km of the coast (Small and Nicholls, 2003). These populations are projected to increase as more people migrate to the coast. This current and projected population will put a strain on coastal ecosystems because of the resources that humans extract from the coast as well as the waste we dispose of in the coastal ocean. Coastal ocean health is critical for human health because humans are exposed to disease causing organisms in this interface (Stewart et al., 2008). Therefore, it is essential to improve existing and develop new coastal management techniques and strategies in order to protect the world's most critical ecosystems (Boesch et al., 2000). Quantifying coastal ocean currents is one such tool to manage the ecosystem. There are several different methods in order to accomplish this. Surface drifters (Lumpkin et al., 2013) provide an accurate measurement of surface drift with high temporal resolution. The drawbacks of this platform are the short-lived nature of the surface floats (order 1 month in a given region like those used in the Global Drifter Program or due to battery life like those used by the United States Coast Guard). Acoustic Doppler Current Profilers (ADCPs) provide single-point or along-track velocity current data with high temporal resolution with measurements throughout the water column. ADCPs with a servicing interval on the order of 1 year carry with it the high cost of ship time to deploy and service the mooring. Satellite-altimetry derived currents provide valuable insights on large-scale geostrophic ocean circulation, but satellite observations of currents near the coast are poor for a few reasons: (i) the sampling strategy was not designed for near-coast regions, (ii) altimetry observations are of lower accuracy near the coast due to land contaminations (altimeter and radiometer), (iii) inaccurate removal of atmospheric effects at the surface and incorrect tidal corrections (Vignudelli et al., 2005; Liu and Weisberg, 2007).

Oceanographic HFRs have been identified as a cost-effective complement to *in situ* systems by providing increased spatial coverage (Fujii et al., 2013). The measurement is typically confined to the coastal zone and can be effective to fill the gaps of other monitoring platforms, such as satellite-based sensors, but with much higher temporal resolution. HFR derived ocean surface currents are a remotely sensed measurement typically collected with land-based sensors, which reduces operations and maintenance budgets for collection of the data as compared to ship-based and moored sensors. There have been measurements with HFR in the open ocean aboard large oil platforms (Lipa et al., 1990) but the vast majority of platforms are located along coastlines. Additionally, HFR operates continuously, and with proper maintenance, is capable of observing time-series with high temporal resolution and longtime records (some sites operating for two decades). These measurements allow for both Eulerian and Lagrangian estimates of the flow field (Ohlmann et al., 2007).

Coastal radars typically operate in the HF and UHF radio bands (3–50 MHz), and transmit and receive a ground wave that couples to the salty sea water surface (**Figure 1**). There have been oceanographic applications of sky wave signals (Anderson, 1986; Headrick and Thomason, 1998) but the large size and cost of these systems have not made them a viable option for the oceanographic community. The traditional measurement of the HFR using groundwave propagation is a radial map of currents derived once an hour (**Figure 2**), but higher temporal resolution sampling schemes are occasionally utilized (Piedracoba et al., 2016). Because of the long radio wavelengths at HF (100 m – 10 m) the receive antennas are kept stationary to look in different directions compared to microwave antennas that are typically rotated to determine bearing. Bearing determination, as it relates to measuring ocean surface currents with HFR, describes the method used by the radar to determine direction of arrival of the signal echo. This processing step is divided into two groups, direction-finding and beam-forming (aka phased array). Direction-finding (compact array) radars, such as the Coastal Ocean Dynamic Application Radar (CODAR) SeaSonde

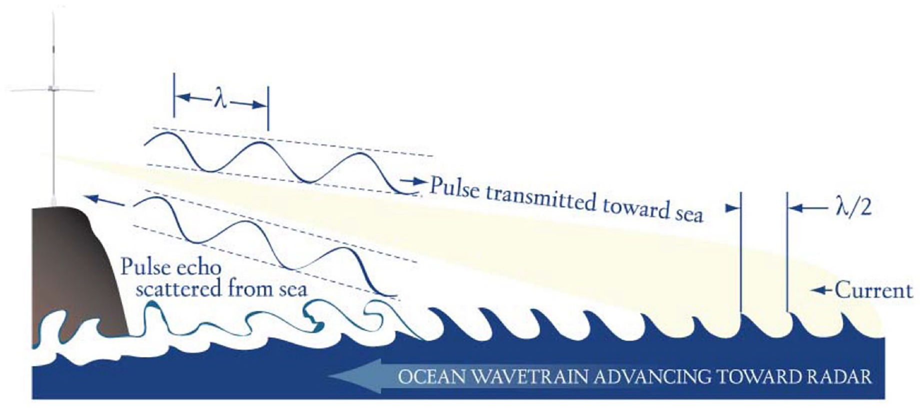

FIGURE 1 | Schematic figure depicting the Bragg scattering process that allows for ocean current measurements with High Frequency radio signals. The echo scattered from the sea is amplified when the transmitted radio signal encounters an ocean wave that has a wavelength that is half the wavelength of the radio signal.

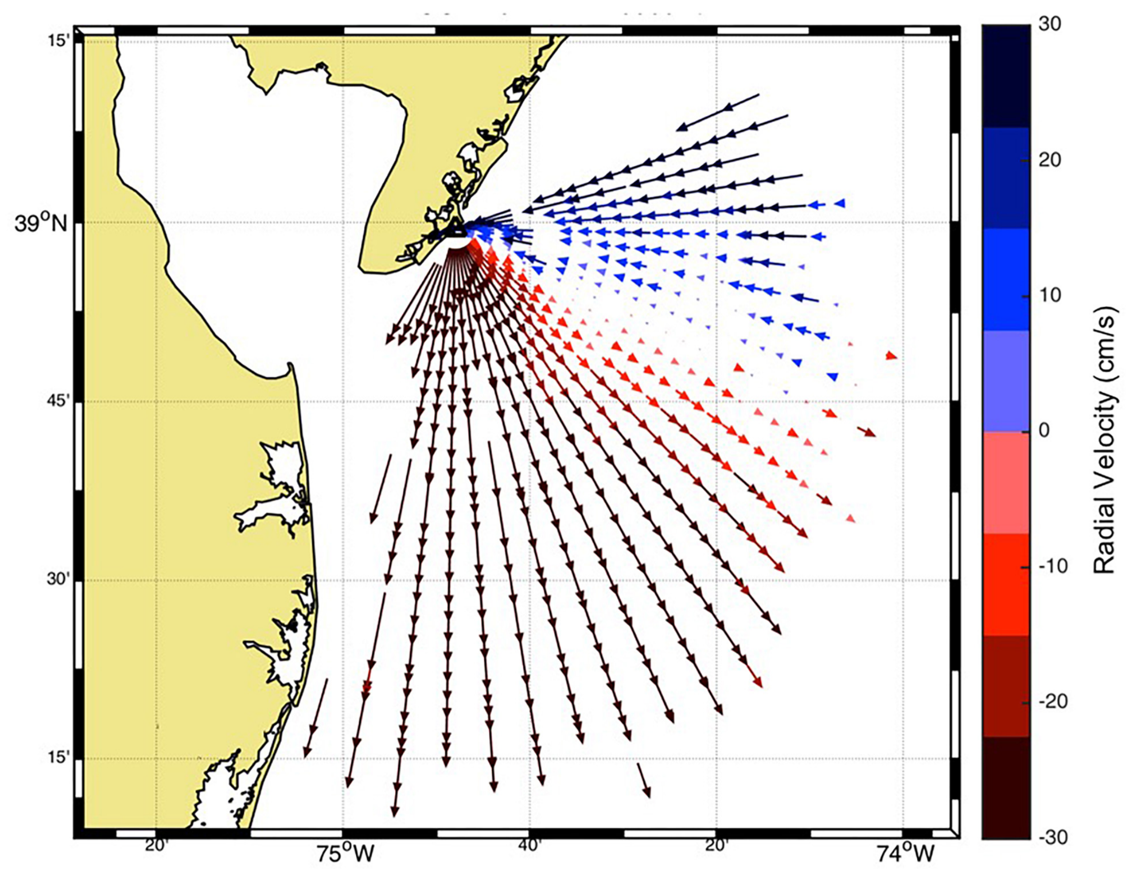

FIGURE 2 | Radial map of ocean currents derived from an HF radar station (triangle). The blue vectors denote surface currents towards the radar station while red vectors show currents away from the radar.

(Barrick and Lipa, 1985), compare the phases and amplitudes of radio signals received by closely spaced antenna elements coupled with various direction-finding inversion algorithms. Beam-forming radars adjust the amplitude and phase of the received signal through an array of antennas to determine bearing (de Paolo and Terrill, 2007). Early versions of this radar type included the Ocean Surface Current Radar (OSCR) and Pisces. The radar models available as of this manuscript with a beam-forming design include the Pisces (Wyatt et al., 2006), the WEllen RAdar -WERA- (Helzel et al., 2007) and LERA (Flament et al., 2016).

Regardless of the manufacturer, the positive contribution of commercial HFR systems to retrieve realistic wave and surface current information has been unequivocally proven.

A recent advancement in the radar technology is the bistatic measurement (Lipa et al., 2009; Baskin et al., 2016) where the transmitter and receiver are geographically separated which yields an elliptical map of ocean surface currents. The radial or elliptical measurements from multiple stations are combined via a variety of combining methods to produce an hourly map of total currents (**Figure 3**) typically, once an hour. An ensemble of total vector files can be used to generate a trajectory model of virtual surface drifters to demonstrate the fate of particles on the surface (**Figure 4**). The readers are referred to Paduan and Washburn (2013) for a thorough discussion of oceanographic HFR theory, development, and applications.

The information contained in the second order region, of much lower amplitude than the first order peak, are utilized to obtain the wave information, i.e., height, centroid period and direction or the full directional spectrum and derived parameters (Wyatt et al., 2011). Wave measurements are obtained using some version of the theory of Barrick (1977). The current techniques for wave measurements range from empirical methods, which relate wave parameters (significant wave height) to an integral of the second order Doppler spectrum, to full numerical inversions, which can provide the ocean wave directional spectrum if the quality of the radar data is good enough. The frequency of the radar determines the maximum and minimum wave height that can be measured by any system. The lower the frequency the higher the wave height that can be measured. For example, the maximum wave height that can be measured at 25 MHz is 4 m however it is 20 m at 5 MHz operating frequency (Lipa and Nyden, 2005). Below the minimum threshold, the lower-energy second-order spectrum is closer to the noise floor and more likely contaminated with spurious contributions that might result in wave height overestimation or limited temporal continuity in wave measurements. Above the maximum threshold, the first-order peak merges with the second-order one and the interpretation of the spectra becomes impossible with existing methods. In this context, recent efforts have been focused on the improvement of wave height estimation for highly variable sea states by using dual-frequency HFR systems (Wyatt and Green, 2009). HFR-derived wave measurements also have a broad range of practical applications and can be used as benchmark for wave model skill assessment (Lorente et al., 2018), as input for assimilation into SWAN or Wavewatch III models (Waters et al., 2013), or for the analysis of extreme wave height events (Atan et al., 2015).

HFR can also be used to estimate wind speed and direction but are not yet robust enough for operational use. The ratio of two first order peaks can be utilized to estimate wind direction (Fernandez et al., 1997; Wyatt, 2018). Estimates of wind speed have also been obtained from the second order peaks (Kirincich, 2016).

The initial "coming of age" for HFR occurred between 2000 and 2010, in which real-time HFR data was accepted as a reliable operational tool. For example, surface current data is ingested in the United States (US) by federal and state group for search and rescue (SAR), oil spill and other operational protocols in coastal waters. Success stories have emerged over the past decade from the United States and elsewhere, as well as examples where the importance of HFR surface currents data was noted (e.g., Deep Water Horizon oil spill in the Gulf of Mexico). The next phase for HFR applications involves the recognition of the value of long-term, high-resolution surface currents for tracking environmental change and marine resources, including coastal water quality, coastal ecosystems and fisheries. This second coming of age is imminent with data sets of over 10 years now available from the west and east coasts of the United States as well as from northern Japan.

The Global High Frequency Radar Network was established in 2012 as part of the Group on Earth Observations 2012–2015 Work Plan (Roarty et al., 2014). A series of meetings were held to jump start the collaboration England 2012, Norway 2013, Taiwan 2014, Crete 2015, and finally the United States in 2016 (Roarty et al., 2016). This series of meetings introduced the radar network to global organizations like the Global Ocean Observing System (GOOS) and the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM). JCOMM coordinates oceanographic measurements, data and services between the Intergovernmental Oceanographic Commission (IOC) and the World Meteorological Organization (WMO). The GOOS is executed within the IOC. In 2017 the Global HFR Network along with ocean gliders were recognized by JCOMM as an observing network of GOOS.

DEVELOPMENT OF NETWORKS

Academic, government, and private organizations from around the globe have established high frequency radar (HFR) networks at regional or national levels to support scientific and operational activities along the coast. The growth of the network remains steady with approximately 400 stations currently operating and collecting real-time surface current information. There are approximately 281 sites reporting to the GEO list as of 2018. The United States and Europe have tracked the growth of this sensor technology versus time (**Figure 5**). 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. HFR systems have also been recently installed in South Africa. The number of organizations displaying surface current information on the Global Network page has also increased from 7 in November 2016 to 13 in May 2017. The organizations currently providing surface current information to the Global Network are shown in **Table 1**.

The Global Network has been organized according to the International Telecommunication Union (ITU) regions (**Figure 6**). Region 1 encompasses Europe, Africa and northern Asia. Region 2 covers the Americas and Region 3 comprises southern Asia and Oceania. In 2012 Resolution 612 was passed by the ITU establishing the use of the radiolocation service between 3 and 50 MHz to support (high-frequency) oceanographic radar operations. This was an important first step for the community because it established the importance of HFR to

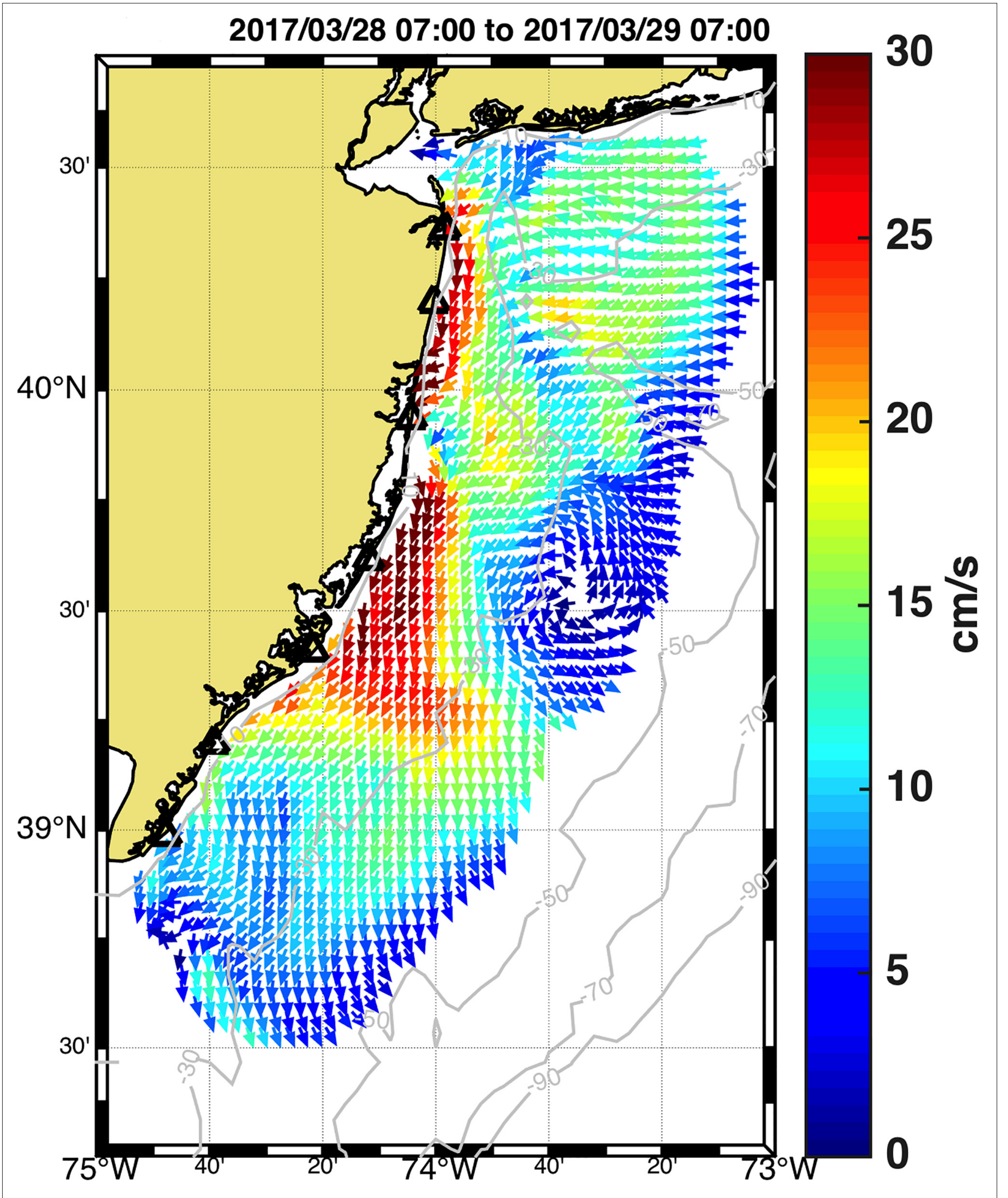

FIGURE 3 | Total Map of surface currents (0–30 cm/s) from seven 13 MHz HF radars along the coast of New Jersey.

receive designation in frequency space for the operation of the radars. There is still more work to be done because while the ITU sets global standards, each region and country within will set specific service rules and licensing regulations. Acquiring a frequency allocation that allows HFR as a primary user is a current goal for the community, as interference within HF bands greatly impacts HFR performance.

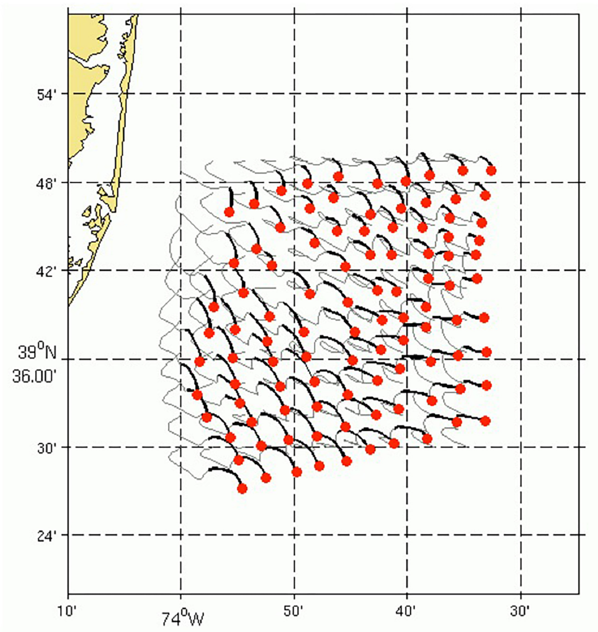

FIGURE 4 | Twenty four hour simulation of virtual trajectories from the surface currents in **Figure 3**. The virtual surface particles (red dots), the trajectory of the particle over the past 24 h (gray line) and the path of the particle over the past 6 h (black line) are shown.

Here is a brief description on the history and present status of HFR networks within the Global regions.

Europe, Africa and Middle East (Region 1)

In Europe (EU), the use of HFR systems is growing with over 62 HFR sites currently operating and a number in the planning stage. A survey to catalog the status of different HFR systems available in the Europe was launched in June 2016 and has been maintained up to date (Mader et al., 2016). The survey gathered responses from 28 European institutions and information on more than 70 HFR systems. From 2004 until 2009 a moderate growth rate of two new HFRs per year was observed and, since 2009, it has increased to around six new HFRs installed per year and up to seven, since 2016 (**Figure 5B**). The most popular identified user of the EU HFR data was academia, followed by European or national maritime safety agencies and weather services (Rubio et al., 2017). The most popular research lines were those related to Lagrangian approaches to surface transport and connectivity (e.g., Menna et al., 2007; Abascal et al., 2009; Uttieri et al., 2011; Berta et al., 2014a; Berta M. et al., 2014b; Bellomo et al., 2015; Solabarrieta et al., 2016; Cianelli et al., 2017), data assimilation and the validation and calibration of numerical ocean forecasting models especially near the coast (e.g., Barth et al., 2008, 2011; Marmain et al., 2014; Stanev et al., 2015; Iermano et al., 2016; Lorente et al., 2016; Hernández et al., 2017) and small scale and mesoscale ocean processes (e.g., Sentchev et al., 2013; Berta et al., 2018; Hernández-Carrasco et al., 2018; Rubio et al., 2018a).

The European contribution to the Global Network is on a volunteer basis and no dedicated funding is allocated directly to the providers for a coordinated effort. The European coordination of HFR systems started with the EuroGOOS HFR Task Team (TT) in 2014, which increased the global visibility of the European HFR systems and enabled a joint integration

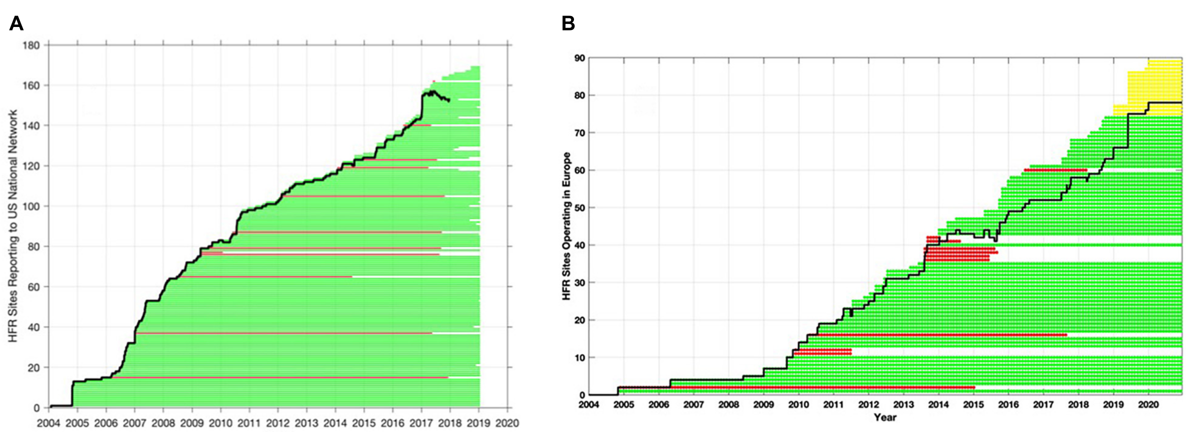

FIGURE 5 | Growth of HF radar networks in the past two decades. **(A)** Number of radar stations reporting to the United States National Network (bold black line) from 2004 to 2018. **(B)** Temporal evolution of operational HFR systems in Europe from 2004 to 2022 (bold black line). The timeline of each of the HFR installations is provided by the discontinuous horizontal lines. Past systems or those no longer providing operational data are plotted in red, future deployments in yellow and operational systems in green.

TABLE 1 | List of countries and organizations providing surface current information to the Global HF Radar Network.

Number	Country	Organization
1	Australia	Integrated Marine Observing System
2	Canada	Ocean Networks Canada
3	Croatia	Institute of Oceanography and Fisheries
4	Germany	Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research
5	Italy	CNR, Consiglio Nazionale delle Ricerche
		OGS, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
6	Malta	University of Malta, Physical Oceanography Unit (PO-Unit),
		International Ocean Institute-Malta Operational Centre (IOI-MOC)
7	Mexico	Observatorio de Corrientes Oceánicas MEXicanas (OCOMEX)
8	Spain	Puertos del Estado
		SOCIB, Balearic Islands Coastal Observing and Forecasting System
		Meteorological Agency *(Euskalmet)*
		INTECMAR
		Universidad de Vigo
		Universidad de Cádiz
9	Taiwan	TOROS (Taiwan Ocean Radar Observing System)
10	United States	Integrated Ocean Observing System (IOOS)

in the Global Network. From its conception the EuroGOOS HFR TT has ensured a close exchange with the GEO Global HF radar network and participated in GEO Global HF radar task meetings. The two European co-chairs of the GEO Global HF radar task are members of the EuroGOOS HFR TT core group, and this institutional collaboration should continue in the future. In addition, the definition of the EU HFR data standard has been developed by the EuroGOOS HFR TT in close collaboration with the EU and US.

In 2018, the HFR EU data node was created as a centralized European competence center to ensure the implementation of the HFR data stream (harvesting, harmonization, formatting, and distribution) from the data providers toward the different EU marine data portals and global data infrastructures. A plan for the inclusion of HFR data into the Copernicus Marine Environment Monitoring Service (CMEMS) through this EU data node is in progress. First steps toward this integration were carried out under the CMEMS INCREASE Project (Rubio et al., 2018b). A survey of the CMEMS community by the INCREASE project highlighted the interest shown in having access to HFR current data at a global level and to operational data derived from the advanced processing of the HFR backscatter signals, such as waves and maps of wind direction, which opens future working lines.

The CMEMS In Situ Thematic Centre (CMEMS-INSTAC), will start delivery of near-real time (NRT) total and radial HFR data from certain sites in April 2019 and April 2020, respectively. The data distribution will be made both at a global and regional level, aiming to foster the relationship between users, providers, and the INSTAC regional components inside the regional alliances of EuroGOOS (ROOSes). Other European HFR operators will be supported in their preparation of their involvement, in order to achieve the final goal of distributing all European HFR data within CMEMS-INSTAC, SeaDataCloud and EMODnet platforms.

Inside CMEMS-INSTAC the HFR data set is considered part of a global product of ocean surface currents, and will be delivered jointly with the global surface drifter data set. The CMEMS structure is thus ready to embrace a global dimension for the HFR data. Work is underway to prepare for the inclusion of United States HFR data from the United States IOOS National HFR Node into the CMEMS-INSTAC Global Distribution Unit, planned for April 2020. This preparation phase is being developed with the MARACOOS (IOOS regional association in the Mid-Atlantic) network and is mainly focused on treating the dataflow and the few discrepancies between United States and European standard data models.

In parallel, the EU Project JERICO-NEXT is working to provide procedures and methodologies to enable HFR data to comply with the international standards regarding their quality and metadata, within the overall goal of integrating the European coastal observatories (Corgnati et al., 2018b).

The ongoing MyCoast project aims to build a coordinated coastal operational observatory in the Atlantic Ocean by improving the synergies between observational and forecasting systems. A dedicated work package is devoted to the analysis and enhancement of HFR-derived wave estimations and the subsequent application to extreme weather events and maritime safety. There is an ongoing effort and a considerable planned investment in the North-Western Mediterranean between Italy and France (Quentin et al., 2017), in the framework of the EU Interreg Maritime Program (projects IMPACT and SICOMAR-PLUS). The plan is to build a network of sixteen HFRs, nine of them already operating, covering 600 km of coastline between the two countries by the end of 2021. The general purpose, through the integration of the HFR data with numerical models and *in situ* measurements, is the development of operational tools in the field of SAR operations and protection of the marine environment. Lastly there is an effort in Europe taking place in the Malta Channel area between Sicily (Italy) and Malta where four HFRs are currently operating as part of the EU Interreg project CALYPSO. Three additional HFRs will be added inside 2019 to the CALYPSO network. The main goal of the CALYPSO project, led by the University of Malta and having the University of Palermo as the main Sicilian partner, is to support efficient response against the threat of marine oil spills and also to support SAR operations and improve security and safety at sea in the *trans*-boundary Mediterranean area between Malta and Sicily.

The reader is referred to Rubio et al. (2017) for a more thorough description of the HFR activities within Europe. Below are descriptions of new networks since this paper was published. In addition, we are aware of installations in Turkey, Israel, and South Africa that will be coming online soon.

Morocco

The National Meteorological Directorate of Morocco (DMN) operates a network of two 5 MHz long-range HFRs (Bouksim et al., 2016) located in the Port of Casablanca and in

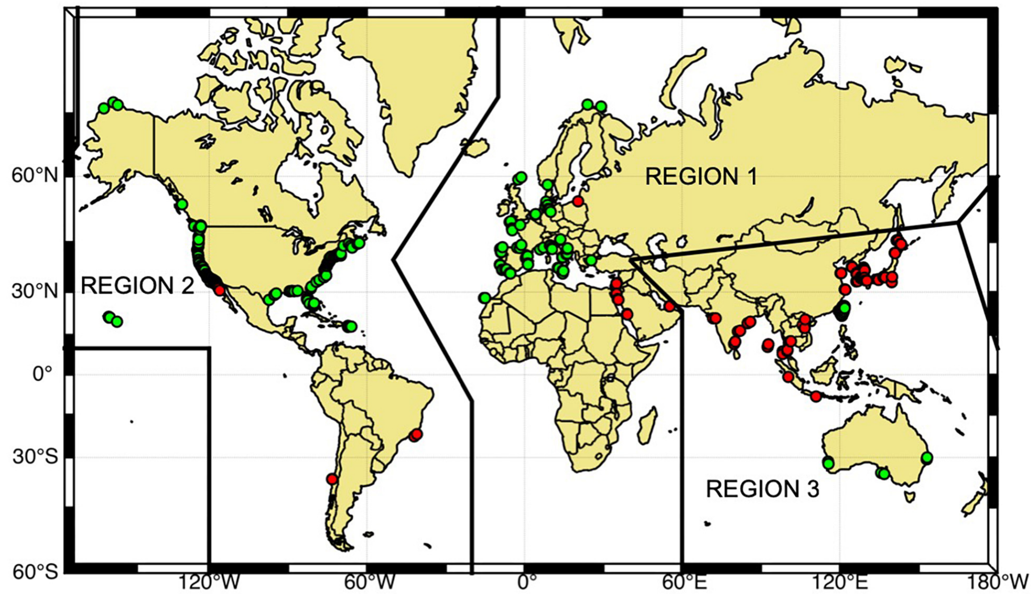

FIGURE 6 | Global distribution of HFR stations organized within the three regions of the International Telecommunications Union (ITU). The green dots indicate stations that are sharing their data through the global network and red dots indicate stations that are not currently sharing their data.

Temara with a measurement range of approximately 200 km offshore, covering an area of around 17,000 km^2 between Casablanca and Rabat. This network was commissioned in April 2016 and represents the first permanent HFR network deployed in Africa. DMN is initially applying HFR surface currents and wave data to validate their operational marine forecast models and to improve their knowledge of the hydrodynamics in this part of the Moroccan coast. In future work, data will also be used for SAR operations, safety in navigation and for better preparedness and response against marine pollution incidents in collaboration with the Royal Moroccan Navy, National Ports Agency and Civil Protection Authority.

Future DMN plans include the extension of the current network to the South to cover the energy port of Jorf Lasfar and the installation of two additional HFRs in Tanger Med and Cap Malabata to monitor the Strait of Gibraltar. Data exchange with Spain is also envisioned to combine data of this new network with the already existing HFR network in this area operated by the Spanish National Harbour Authority (Puertos del Estado) in order to cover the whole strait.

Saudi Arabia

In 2015 King Abdullah University of Science and Technology (KAUST) and Saudi Aramco installed the first HFR network in the Kingdom of Saudi Arabia (KSA), composed of two 16 MHz HFRs, monitoring surface currents and waves in the central Red Sea (Solabarrieta et al., 2018). One HFR is located at a KSA Coast Guard station in Rabigh pairing with the other set on the KAUST campus in Thuwal. Both stations provide hourly surface currents measurements up to a range of 70–100 km with a spatial resolution of 3 km. The network was further expanded in 2017 to the North with the installation of two additional HFRs in Duba and Almuwaylih. KAUST owns two additional HFRs and plans to install these two units in the Southern part of the Red Sea inside 2019. **Figure 7** shows the location of KAUST's current four radar network and envisioned location of the two additional units they plan to deploy in the Southern part of the Red Sea. Current use of the data is restricted to basic science, which will contribute to the Kingdom's fundamental understanding of ocean processes in the region. Some envisioned future applications include tracking of marine pollutants, fisheries management, safety of navigation and the design of marine protected areas.

Portugal

The Portuguese Hydrographic Institute (IH), the main operational oceanography institution in Portugal, operates a network of five CODAR HFRs (Fernandes, 2014). The network consists of two 13 MHz HFRs deployed in 2010 deployed in São Julião and Espichel close to Lisbon and three 13 MHz CODAR HFRs installed along the coast of the Algarve in Vila Real, Alfanzinha and Sagres inside the period 2012–2016 by the TRADE project[1]. The main goal of the TRADE network is to improve safety in navigation and port operations in the Gulf of Cadiz, from the Straits of Gibraltar (Spain) to Cape St. Vicente (Portugal). Use of the Portuguese HFR data includes validation of numerical surface currents models, tracking of marine pollutants and use in SAR cases. A CODAR Tsunami Detection Software Package has recently been also installed on the Sagres HFR station as part of the OCASO project in order to develop tsunami detection algorithms that are adapted to the very complex bathymetry of the area. The IH has a mid-term plan to extend its HFR network to a total of 20 stations.

[1] http://www.tradehf.eu

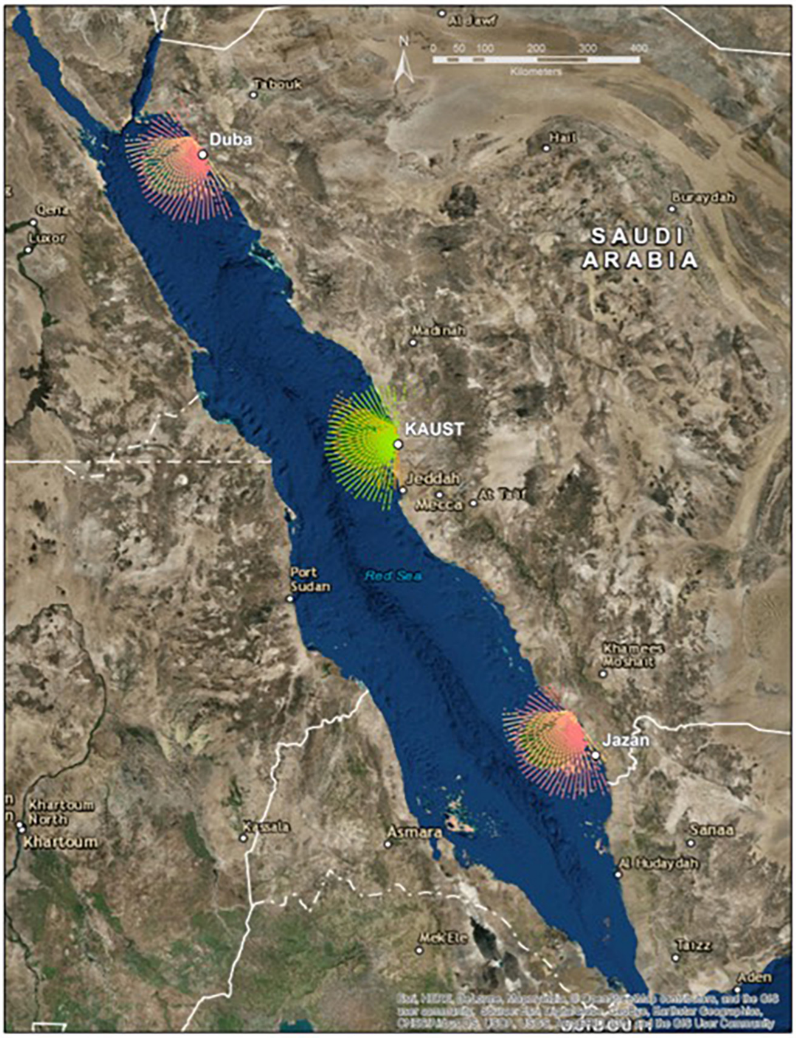

FIGURE 7 | HFR Network off the west coast of Saudi Arabia. The colors indicate typical radial coverage for the 6 HFR stations.

The Americas (Region 2)

Canada

Historically, Canada's coastal HFR activities have focused on vessel detection using phased-array systems on the Atlantic coast (Ponsford et al., 2003). This research and development continues as a component of Canada's defense research programs, but as of 2018 only one of Canada's 22 coastal HFRs falls within this category with an equal number of HFRs on the Pacific and Atlantic coasts. Sixteen of the HFRs are owned by universities and all but three are operated by universities. We make this distinction because the future of coastal HF radar in Canada is influenced by the fact that all of the existing radars and networks are research based and therefore financed through various finite research programs, as opposed to being components of the nation's operational maritime monitoring and surveillance infrastructure.

From an application perspective, vessel detection has the longest track record in Canada, but has yet to emerge from the R&D stage. Defence Research and Development Canada (DRDC)-Ottawa and Raytheon Canada Limited worked cooperatively for decades to develop over-the-horizon, phased-array HFR to detect vessels up to 200 nm from shore. Currently, DRDC Ottawa operates a 3rd generation HFR installed in 2015 near Halifax, Nova Scotia, Canada. The radar includes a spectrum management scheme that allows operation on a non-interference-basis.

Another defense research agency, DRDC Atlantic, is working cooperatively with Dalhousie University and the Marine Environmental Observation Prediction and Response (MEOPAR) Network, with a focus on oceanographic applications. Dalhousie is operating two of DRDC Atlantic's 5 MHz HFRs, which were installed in 2014 near Halifax, Nova Scotia, on either side of the above referenced phased-array system owned by DRDC Ottawa. Dalhousie uses surface current data in its coastal circulation and ocean forecasting models. Its Department of Oceanography works cooperatively with Canada's Department of Environment and Climate Change, which is home to the nation's weather forecasting programs and operations. The Atlantic Pilotage Association has also expressed interest in this Halifax R&D network, but from a wave monitoring perspective in support of ship traffic operations.

On the Pacific coast, Ocean Networks Canada (ONC) (Heesemann et al., 2014) and the Department of Fisheries and Oceans own and operate coastal HFRs at various locations. ONC operates a WERA at Tofino (installed 2016), on Vancouver Island, four CODAR HF radars covering the Strait of Georgia (2011, 2012, 2016), and two CODARs covering Chatham Sound off Prince Rupert (2016, 2017). The WERA unit is used by German and American researchers to develop tsunami-detection algorithms. The CODARs are used by research programs run out of the University of British Columbia and the University of Victoria, but also by researchers located in Korea, China and other parts of Canada. There are also two ONC CODARs overlooking the Strait of Juan de Fuca, not fully installed, that await spectral allocation, and the Department of Fisheries and Oceans operates two long-range CODARs on either side of Hecate Strait (installed 2017). The Canadian Coast Guard has expressed interest in using surface current products arising from these and other Canadian HFR.

The longest running coastal HFRs in Canada are owned by the University of Maine, which since 2004 has operated a long-range CODAR in Nova Scotia and another in New Brunswick. Memorial University operates two WERA-like HFRs in Placentia Bay, Newfoundland, and the Université du Québec à Rimouski operates two standard CODARs and a WERA on the St. Lawrence River estuary.

Chile

Sixteen counties of the Chilean Biobío Region share a border with the ocean, where important sea related economic activities are performed, among them fisheries, navigation, international commerce, infrastructure, defense, tourism, and recreational activities. Historically this region has been affected by natural disasters related to the ocean such as wave surges, heavy weather, tsunami, oil spills, sinking of ships, etc. causing strong social, economic and environmental damages. Several of these risks are associated with physical properties of the coastal waters such as sea waves, surface winds, and marine currents. The solution for these challenges is being answered by the Chilean Integrated Ocean Observing System (CHIOOS). The CHIOOS is based upon two WERA High Frequency (HF) ocean radar systems, which are installed along the coast and provide real-time measurements of physical properties of the coastal waters, and complemented by sensors for relevant biological and chemical ocean parameters. This project will be carried out in strong collaboration with Chilean national and regional agencies, among which are the Chilean Navy National Hydrographic and Oceanographic Service (SHOA), the Chilean Emergency Regional Office (OREMI), the local Maritime Authority (Gobernación Marítima de Talcahuano), the national Ministry of Energy, municipalities of coastal counties, and harbor authorities[2].

Mexico

The Mexican HF radar Network has its origin starting in 2003, when the Autonomous University of Baja California (UABC) acquired two SeaSonde CODAR systems, which were operational from 2003 to 2005 on Rosarito Baja California. Later in 2005 another two WERA type radars were purchased through a research project funded by the Concejo Nacional de Ciencia y Tecnologia (CONACyT, National Council of Science and Technology). Those two radars were installed in the Gulf of Tehuantepec, and were operational for almost 3 years (Flores-Vidal et al., 2014).

Those early installations in Mexico had a completely oceanographic research purpose (Flores-Vidal et al., 2011, 2013, 2018) but lacked operational continuity with gaps in the time series on the order of two to 3 months for the worse cases, and with absolutely no real time data transfer. In 2009 the four radars from UABC were installed in Todos Santos bay (100 km south from the United States-Mexico border) and for the first time provided a continuous real-time time series with reduced data gaps due to the ability of data quality control 24/7. The Mexican secretary of Marine corps (SEMAR) used the data during surveillance and SAR operations. In 2010 the Observatorio de Corrientes Mexicanas OCOMEX was created and obtained funding from CONACyT to purchase three more radars which were installed on Baja California producing long-range (∼200 km offshore) with time-spatial resolution of 1 h and 3 km and real-time support. Up to today OCOMEX is still operational, producing two nested grids of sea surface currents, inside the Todos Santos Bay with resolution of 500 m and 15 min, and at the adjacent ocean (Southern California Coastal Current) with 3 km and 1 h of resolution (**Figure 8A**). With almost 10 years of measurements with research purposes on the southern California shore (Flores-Vidal et al., 2015, 2018) has brought operational success which supports Mexican federal agencies as well as the academic sector.

In 2015, the Mexican Secretary of Energy (SENER) along with CONACyT launched an unprecedented program for research, surveillance and mitigation in case of oil-spill in the Gulf of Mexico. UABC and OCOMEX were funded to purchase and install 15 radar units on the Gulf of Mexico. OCOMEX decided to install LERA radars (Flament et al., 2016) due to its performance, robustness, compact, and low power consumption design. Presently, the OCOMEX-UABC team operates 16 HFR in the Gulf of Mexico, spanning the states of Tamaulipas, Veracruz, Tabasco, Campeche, and Yucatan (**Figure 8B**). The installation, management and maintenance of this HFR network is being performed by a multi-institutional consortium which include more than 20 universities and research institutes in Mexico. Currently, OCOMEX operates 22 near real-time (NRT) HFR systems in Mexico and is actively working with United States-IOOS personnel to establish a relay to the HFRNet.

[2]www.chioos.cl

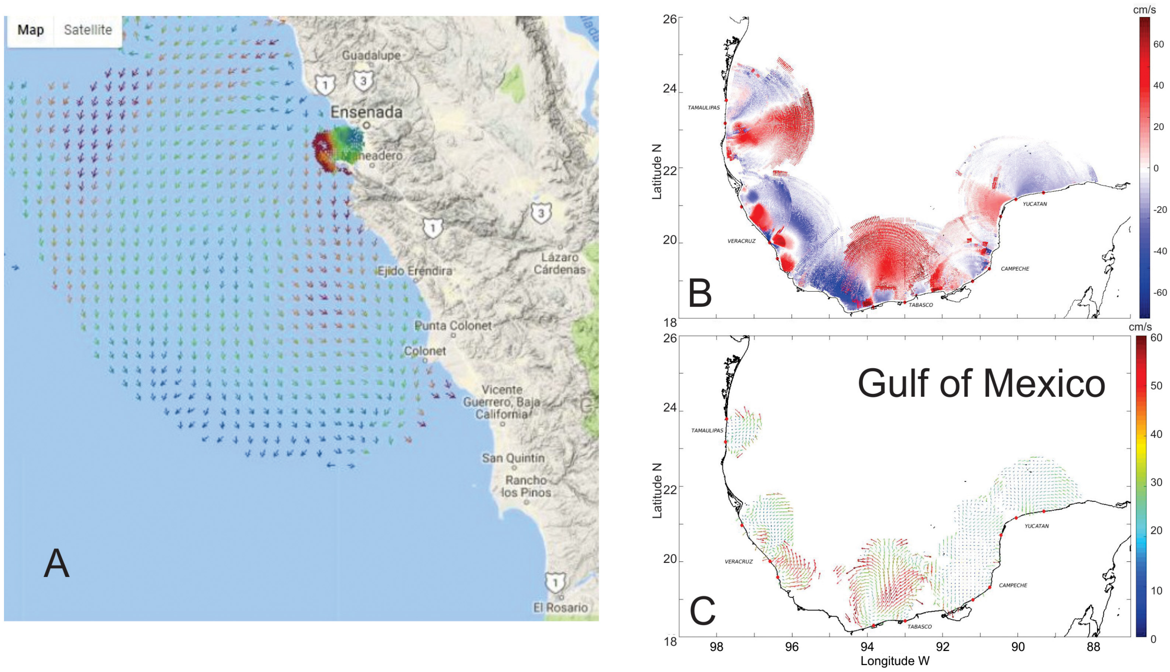

FIGURE 8 | (A) Sea surface currents mapped at high resolution (400 m and 15 min, respectively) inside of Todos Santos Bay, along with long-range (–200 km offshore) measurements simultaneously taken at the adjacent open ocean. Long-range measurements have a time spatially resolution of 3 km and 1 h, respectively. **(B)** Map of 11 radar stations (red dots) installed in the Gulf of Mexico from 2017 to 2018 showing radial currents toward the radar station (red) and away from the radar station (blue) **(C)** the radial measurements from **(B)** are combined to generate total vector currents between 0–50 cm/s.

United States

In 2004 the United States led Integrated Ocean Observing System (IOOS) established a national network of HFR sites along the coastal United States, frequently referred to as the National Network (Harlan et al., 2010). The National Network differentiates sites by geographical area including the United States West Coast (USWC), United States East and Gulf Coast (USEGC), Hawaii (USHI), and Puerto Rico and Virgin Islands (PRVI). Additionally, when weather conditions allow (typically during summer months), HFR sites from Alaska North Shelf (AKNS) and Gulf of Alaska (GAK) are included. The technical basis of the National HFR Network was guided by a steering team of experts in the field, with the resulting documentation distilled into a National Surface Current Plan (U.S. Integrated Ocean Observing System [IOOS], 2015) which has been updated occasionally since its initial publication. The plan describes the design and implementation of the National HFR Network from the infrastructure of individual HFR stations, data management and dissemination, and HFR related product development. The report highlights the requirement to collect surface current given its societal importance, and established priority for the location of HFR stations within eleven regional associations (RAs) which guide development of regional ocean observing activities. Furthermore, the plan provides technical design of the National Network to acquire radial current maps from individual HFR stations, process the radial maps into a Real Time Vector (RTV) product and establish requirements for data standards, management and distribution, while providing a metric of performance which is monitored daily. The report also recognized the importance of staffing structure through academia/federal partnerships.

The HFR National Network began collecting radial current maps from participating regions in 2006 (**Figure 9**). The geographic coverage for each region over the entire period of recording is shown for the main regions. Surface currents collected through IOOS HFR National Network are utilized by a number of federal agencies including United States Coast Guard (Search and Rescue), NOAA's Office of Response and Restoration (OR&R) (hazardous spill response), National Ocean Service Center for Operational Oceanographic Products and Services (CO-OPS) (ocean tidal prediction), as well as state and local agencies that use data in water quality management. Additionally, surface current data is distributed to various research and development groups that are assimilating HFR derived surface current into numerical models. The United States West Coast Ocean Forecast System (WCOFS) is developing a capability to assimilate HFR surface currents into the 2-km horizontal resolution, ROMS based numerical model run along the entire United States West Coast (Kurapov et al., 2017). Finally, the IOOS-funded Short-term Prediction System (STPS) uses real-time analysis of the HFR surface currents to predict trajectories that are fed to the United States Coast Guard SAR tools (Roarty et al., 2010; Harlan et al., 2015).

Asia and Oceania (Region 3)

The status for HFR for Australia, China, Japan, Korea, and Taiwan was documented recently (Fujii et al., 2013). Here are recent advancements for some of these countries as

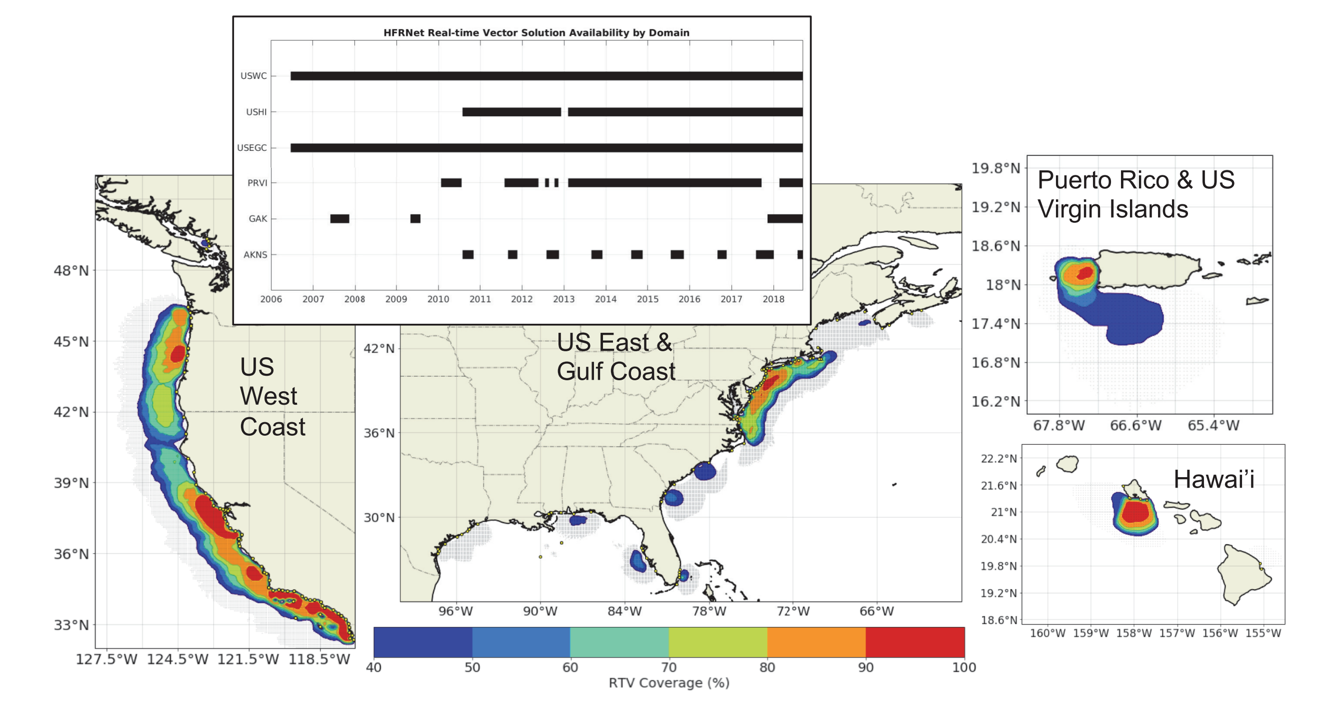

FIGURE 9 | Temporal and spatial coverage of United States IOOS HFR National Network by region since 2006.

well as a description of HFR in the recent networks of Vietnam and Thailand.

Australia

The Australian Ocean Radar facility, based at the University of Western Australia is part of the Integrated Marine Observing System (IMOS), a national collaborative research infrastructure tasked with collection and dissemination of ocean data. The radar facility uses commercial direction-finding (SeaSonde) and phased-array (WERA) HFR systems. Each HFR node is configured primarily to sample ocean currents with a maximum range of over 200 km. Radar data, freely available from the IMOS portal[3], are used for scientific research, operational modeling, coastal monitoring, fisheries and other applications (Kerry et al., 2016; Mihanovic et al., 2016; Archer et al., 2017, 2018; Mantovanelli et al., 2017; Schaeffer et al., 2017; Wandres et al., 2017). Between 2017 and 2018 asset relocation across the country was conducted, aimed at maximizing HFR coverage at a regional scale, and increasing data uptake. A new regional node was added to the network north of Sydney (New South Wales) composed of long-range (5 MHz) SeaSonde HFR systems, became operational in December 2017 but soon caused interference problems to primary users and has since been operated below its capabilities. The transmit power was reduced, typically below 1 Watt and sweep width reduced to less than 50% of the ITU allocated bandwidth, yet these settings were still causing interference to several users across the country. To date, operational uptime at this location is less than 50%. The spectrum management agency within Australia (ACMA) is now enforcing a full implementation of ITU resolution 612 before operations can be resumed at this location. These requirements now include use of a directive transmit antenna, reduced bandwidth and employing a technique to allow multiple radars to operate on the same frequency. In 2018, the Federal Government approved operations for the 2018-2022 time period with potential to continue operation for additional 5 years, providing operational budget and injection of significant funds for the refurbishment and upgrade of the entire HFR systems, and replacement of the aging infrastructure. Additionally, the relocation of a decommissioned phased array HFR node from Queensland to the northwest shelf of Western Australia was approved through co-investment between IMOS and the oil and gas industries in the area, in support to development of an ocean monitoring tool for the Ningaloo reef, a world heritage area.

[3]https://portal.aodn.org.au/

Vietnam

Analysis of the spatial and temporal ocean circulation patterns of the Gulf of Tonkin are the focus of an ongoing collaborative effort between the Vietnamese Center for Oceanography (CFO), Vietnam Administration for Seas and Islands (VASI), and United States partners. Three long-range HF radar sites were installed in the spring of 2012 within the Gulf of Tonkin, Vietnam (**Figure 10A**). The temporal availability and spatial coverage of the radial data were strongly dependent on the seasonal monsoon cycles that drive observed circulation patterns within the predominantly low energy environment of the Gulf of Tonkin. Minimal radial coverage occurred during the summer monsoon seasons due to prevailing weak offshore wind directions. The

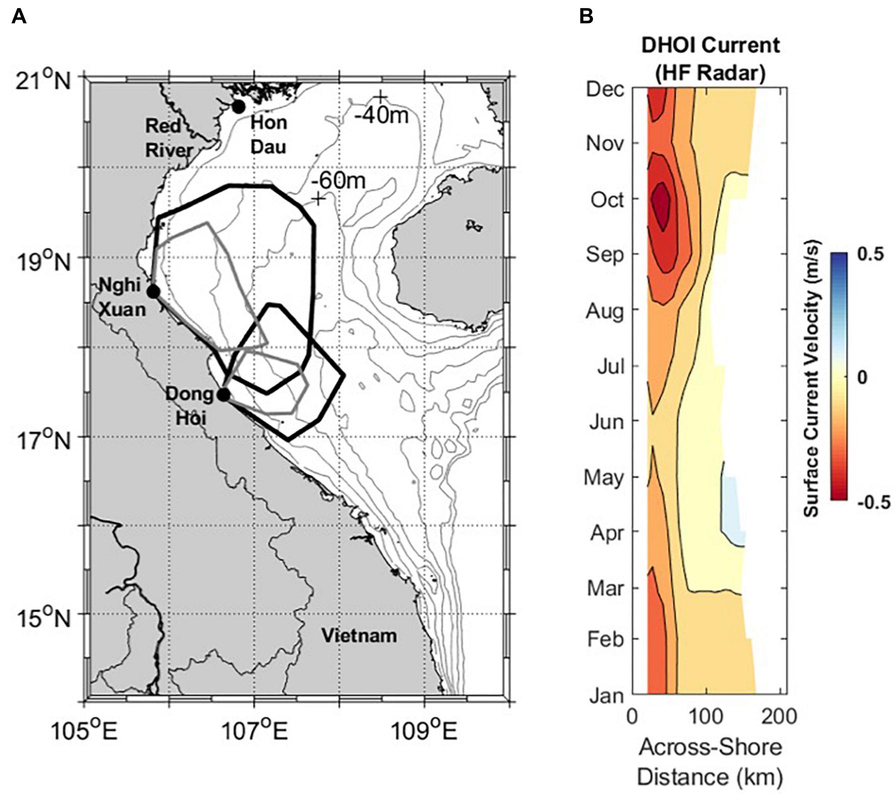

FIGURE 10 | (A) Map of Vietnamese coastal waters with HFR stations (black dots) overlaid with 20 m depth contours. The polygons indicate the 50% radial data coverage boundaries of the HF-radar during the winter season (black line) and summer season (gray line). **(B)** Hovmoller diagrams of HF radar alongshore surface currents located just north of the Dong Hoi radar site. Positive currents indicate poleward flow while negative values denote regions of equatorward flow. HF radar monthly averages are computed from a 2 year period from June 2014 to June 2016.

onset of the winter monsoon season results in a transition to an onshore flow resulting in better temporal availability and spatial coverage of radial data (**Figure 10A**).

Numerical simulations confirm coastal flows, originating from the Red River, are a prominent feature impacting the circulation of the western region of the Gulf of Tonkin. Two years of monthly averaged HF radar observations, from June 2014 through July 2016, were used to assess the seasonal temporal and spatial variability of coastal currents. The upcoast/downcoast surface currents along a shore normal 200 km transect just north of the Dong Hoi radar site for this period illustrates seasonal fluctuations in the coastal current that are consistent with model results (**Figure 10B**).

As a result of the successes from the United States – Vietnamese partnership, future efforts will build on the developed relationships to continue education and training in the use of emergent ocean technologies. This will include working with VASI and CFO as they begin to further develop their HF radar infrastructure along the Vietnamese coast.

Korea

As Korean economy has increased, the importance of NRT surface currents measured in coastal and marginal seas around Korea has been recognized since 1995. Pukyoung National University (PNU) first installed HFR systems in the southeast coast in 1999 to monitor the East Korea Warm Current (EKWC). HFR systems gradually increased with oceanographic demands for 10 years (**Figure 11B**). The HFR network rapidly expanded from 9 radar sites in 2009 to 46 sites in 2016 in order to respond to increasing demands of the current data covering large areas with increased spatial and temporal resolution for fishing activities, maritime transportations, coastal zone developments and harbor constructions, and coastal environment managements.

The Korea Hydrographic and Oceanographic Administration (KHOA) has been focused on operational application of radar-derived currents around six major harbors with 31 HFRs where ship traffic is heavy, providing NRT data to the public and wide variety of end-users. Universities and research institutes have mainly applied HFR systems to scientific researches. Kunsan National University (KNU) has installed radars to examine the effects of large coastal development on the current structure and variation of river plumes (Son et al., 2007; Lee et al., 2013; Kim et al., 2018) and the observation-based current variabilities for the effective management and utilization of the mid-west coastal sea in the future. Seoul National University (SNU) has operated HFRs to map surface current along the mid-east coast where the East Korea Warm Current (EKWC) and North Korea Cold Current (NKCC) meet and frequently produce complicated

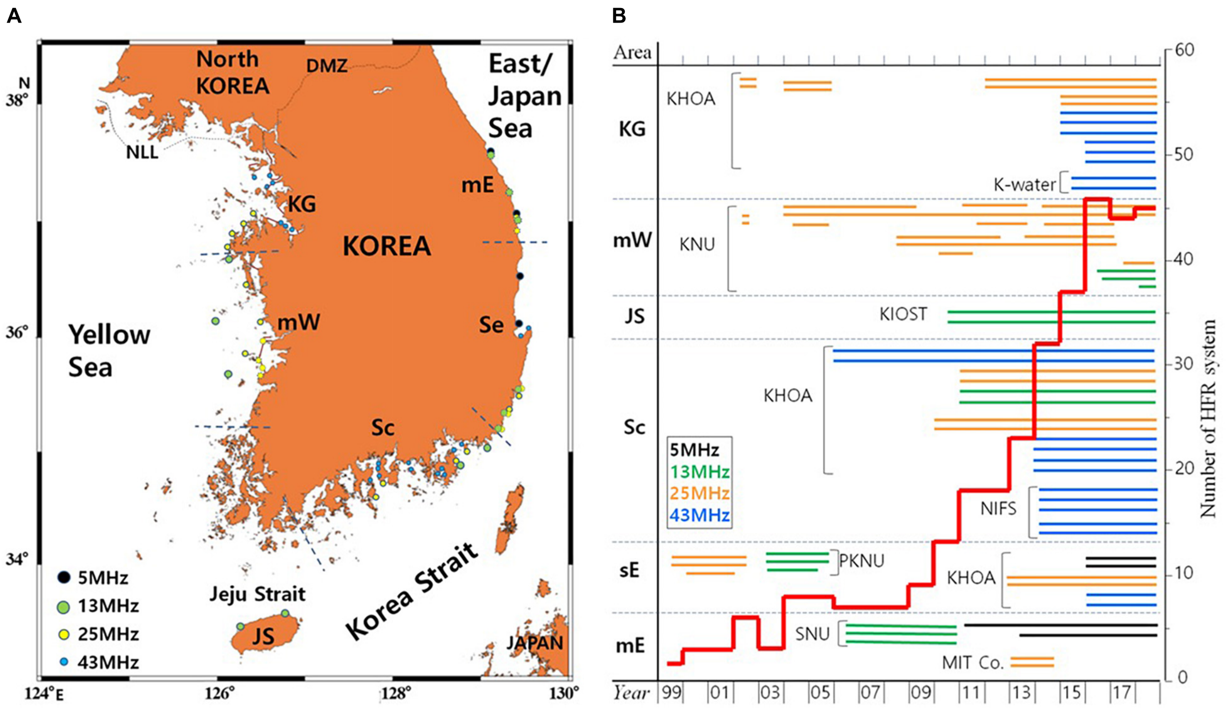

FIGURE 11 | (A) Locations HFR sites observing surface current around Korean coast that is divided into 6 areas with abbreviated coast-name, KG, Kyug-Gi bay; mW, mid-west coast; JS, Jeju Strait; Sc, South coast; Se, south east coast; mE, mid-east coast. Circles with dotted line denote the closed sites. **(B)** Number of radar sites operated by Korean organizations from 1999 to 2018 (bold red line). Capital characters indicate the abbreviated name of HFR operating organizations (see the text for full name).

flow patterns. Korea Institute of Ocean Science and Technology (KIOST) has operated two radars (13 MHz) since 2012 to observe the current structure and variability in the Jeju Strait. National Institute of Fisheries Science (NIFS) has operated an HFR network since 2014 to investigate the dispersion and residence time of pollutant materials in the inner bays along the south coast in order to plan the sanitation management and space requirements for aquaculture farms. Korea Water Resources Corporation (K-water) has monitored the outflow jet from the gate of Shihwa lake tidal power station to estimate effects of the jet flow on the coastal environment since 2015. Marine Information Technology Co. (MIT) has mapped currents and waves off the mid-east coast from 2013 to 2014 for a meteorological demand using the two HFRs that are a unique WERA system in Korea.

With the increase of HFR systems, the Korean HFR community recognized the necessity of cooperation between organizations to share experiences and information about radar operation and promote the efficient use of radar-derived data. The Korean Ocean Radar Forum (KORF) was established in 2011 for this purpose. KORF holds a workshop every year, and discusses issues that are common to operators and end-users in Korea. In May 2012, KORF organized the 1st Ocean Radar Conference for Asia-Pacific (ORCA) in Seoul Korea to share experiences on HFR network planning, operation, maintenance and data management, exchange ideas about application and research results, and build relationships across national boundaries (Lee and Heron, 2013; Fujii et al., 2013). More than seventy persons from ten countries participated in the 1st ORCA and the conference has been successively held every 2 years.

Though 45 HFRs are presently operating in the Korean coast for public and scientific usages, partnership between KORF members has not established yet to organize a nation-wide data node to systematically respond to a wide array of end user's demands. Recently the Korean government recognized HFR as a valuable platform for building wide integrated surveillance of marine territory and launched a research project integrating satellite, AIS, HFR, UAV etc. data and platforms. The Korean HFR community is trying to establish a national organization to collect HFR-data to a data aggregation node, support technical and operational design for data standards, management and distribution, raise funds for a national network installation, and participate to the international observing programs over the next decade.

Thailand

Thailand first began installing HFR systems in 2012 and are operated under the responsibility of Geo-Informatics and Space Technology Development Agency (GISTDA), which is located within the Ministry of Science and Technology. The purpose of the project is to understand the circulation pattern and wave characteristic in the Gulf of Thailand in both time and space continually in order to support the government's water management system from land into the coastal zone. The coastal radar systems in Thailand use frequencies of 13 and 24 MHz covering the Gulf of Thailand and Andaman with a total of 19 stations. Installing the system was divided into two phases, consisting of the first phase from 2012 to 2015 which installed 13 stations in the Gulf of Thailand and the second phase from 2016 to 2018 which installed 4 stations in the Gulf of Thailand and 2 stations in the Andaman Sea. The HFR platforms in Thailand have also been outfitted with closed circuit television for displaying of wave and weather conditions to the public.

Geo-Informatics and Space Technology Development Agency has developed geographic information systems that integrate satellite imagery, coastal radar surface currents and other related remote sensor to monitor marine and coastal environments in the Gulf of Thailand and Andaman sea. This integrated product is paired with a vessel tracking system to analyze marine pollution by modeling the pollution situation and direction. These data are used as a tool for analyzing pollution sources, planning and situation management, including marine pollution alerts from oil spills or phytoplankton blooms. The HFR data is also utilized for monitoring waves and currents which are the factors affecting coastal zone change in Thailand, as well as for integrating approaches, project plans and budgets for coastal erosion management. Lastly, integration of coastal radar data with satellite imagery data and other information such as sea temperature and chlorophyll content for is helping fisheries management, water quality monitoring and marine resource conservation in Thailand.

Information from coastal radar systems has been used by government agencies, educational institutions, the private sector and the general public by accessing to the data via web-based applications and mobile applications. The development of coastal radar systems in Thailand under the implementation of GISTDA is another useful remote sensor for coastal area management. The application of this technology not only fulfills the mission of GISTDA, but it is a response to the mission of all marine and coastal sectors in Thailand. The use of such systems is diverse and focuses on the overall strategy of the country. Based on our past performance, lowering system maintenance costs is very important and future plans, we will continue to focus on the development of systems based on the integration of GISTDA and partner agencies expertise in geospatial information systems (GIS, satellite imagery, GNSS, remote sensors) to enhance capability of the people and coastal communities to utilize and access this information in order to improve the quality of life and safety in our coastal waters.

Taiwan

Taiwan is an island on the margin sea between the western Pacific and the Eurasian shed. The interaction between the ocean and the residents is very close. The first set of HFRs introduced in Taiwan can be traced back to the 1990s. The Naval Meteorological and Oceanographic unit was responsible for operating the HFR system. They were expected to provide over-the-horizon ocean surface currents and wave information for the battlefield. Later, at the initiative of ocean scientists and disaster prevention experts, government departments such as science and technology, education and transportation systems launched projects for the construction of High Frequency surface wave radars for ocean monitoring beginning around 2010. As of 2018, includes: 19 HFRs are operated by TOROS (the research organization for the establishment and maintenance of marine radars within the Taiwan Ocean Research Institute), two HFRs operated by the Naval Academy (called SCONET) and the two phased array radars operated by the Harbor and Marine Technology Center. Over the past 8 years these radar systems have provided continuous, NRT surface current maps of the surrounding waters around Taiwan and sea state information for the 14 commercial harbors and 225 fishing ports. The HFRs have played an important role in marine environmental information for coastal ocean science research, navigation or recreational safety, and maritime SAR.

Therefore, starting in 2019, the Central Weather Bureau of the Ministry of Transportation and Communications will construct an observation network consisting of three phased array radars in the northern Taiwan Strait to provide metocean information needed for transportation safety. The Harbor and Marine Technology Center will also implement a phased array radar in central Taiwan to monitor the sea state and vessel status within an offshore wind farm. Another network being developed entails monitoring the Luzon Strait between Taiwan and the Philippines which will form the Luzon Strait Ocean Observation System (LuSOOS).

DATA PRODUCTS, QUALITY CONTROL, AND DISSEMINATION

Deployment and Maintenance Best Practices

Given the need to collect high-quality observations from a number of independent organizations at varied coastal locations, IOOS has supported HFR technical and operation staff under the Radiowave Operators Working Group (ROWG). Founded in 2005 this group maintains an informational wiki[4] (password protected), email list, and computer code repository[5]. The group is open to HFR operators from the United States and international institutions and meets frequently to discuss standard practices, maintenance concerns and technology updates. The group has encapsulated best practices for HFR equipment setup and required maintenance into a living document called Deployment & Maintenance of a High-Frequency Radar for Ocean Surface Current Mapping: Best Practices (Cook et al., 2008). Topics include site setup of HFR equipment, power and cooling considerations, software/hardware configuration, data management and site maintenance. Additionally, HFR vendors provide guidance to HFR operators to assist with the goal of collecting the highest quality data as different locations may have specific issues and concerns and there is no "one size fits all" approach to HFR site deployment.

[4]http://rowg.org
[5]http://github.com/rowg

In Europe, the EuroGOOS HF Radar Task Team was established in 2014, with the goals of: (i) promoting joint progress through networking and scientific synergies for key questions; (ii) developing best practices and tools exchange; (iii) improving administrative procedures and regulations (e.g., the cross-border agreement for oceanographic radars in the 13-16 MHz band operating in the Western Mediterranean Sea in Spain, France and Italy was signed in February 2018); (iv) looking for complementary of HFRs with other multi-platforms and model products[6]. Simultaneously, definition of best practices in the implementation and use of HFR systems as well as the testing of methodological improvements on HFR retrievals and products is reported in the context of JERICO-NEXT project.

Dealing with one of the main risks foreseen in order to ensure HFR sites sustainability (i.e., downtime, outages and failures), the EU HFR data node, aligned with the leading efforts of MARACOOS, have shared best practices for the creation of HF Radar outages database (Updyke, 2017) as an aid for operations and maintenance. In spite of the fruitful collaborations between the HFR national networks, operators recognized the necessity for a centralization of methodologies and best practices documentation to increase efficiency, reproducibility and interoperability of the coastal HFRs network design, operation and maintenance tasks, In this context, the Ocean Best Practices (OBP) System[7] is emerging as the unified, sustained and readily global accessible knowledge based of interdisciplinary best practices in the ocean observing value chain to foster innovation and excellence. Particularly, in the case of HFR, best practices documentation related to the EU network current status, QA/QC HFR surface current data, deployment & setup of HFRs and HFR data management are currently available at the IODE OBP repository[8]. Nevertheless, an extra effort is required from the global HFR network to document best practices and to promote their propagation. Moreover, the involvement of HFR experts from different networks may contribute to the internal peer-review of best practices documents.

Quality Assurance/Quality Control

Within the United States, IOOS strives to collect the high-quality data for 34 identified core variables, which include ocean currents. To this goal, the Quality Assurance/Quality Control (QA/QC) of Real-Time Oceanographic Data (QARTOD) Project Plan was finalized in 2012, and established quality control procedures for the 26 core variables representing physical, chemical, biological, and multidisciplinary ocean observations (U.S. Integrated Ocean Observing System [IOOS], 2017). Coordinated effort between manufacturers, academic researchers and federal scientists created the Manual for Real-Time Quality Control of High Frequency Radar Surface Current Data published in 2016 (U.S. Integrated Ocean Observing System [IOOS], 2016). The manual incorporates existing QA/QC procedures from a group of HFR experts, and identified a number of tests to ensure QA/QC of both radial current measurement and total current vector measurement. Efforts to implement these tests in the real time data stream are ongoing and occurring at the radial current collection sites, and at the National Network.

In order to deliver high quality HFR data for scientific, operational and societal applications and to enforce discovery and access for HFR data, the European HFR community defined a standard model for data and metadata for producing NRT HFR surface current data, aimed at ensuring efficient and automated HFR data discovery and interoperability. This data model will be the operational data delivery model since the entry in service of HFR data distribution in CMEMS-INSTAC occurs in April 2019. The model has been implemented according to the standards of Open Geospatial Consortium (OGC) for access and delivery of geospatial data, and compliant with the Climate and Forecast Metadata Convention CF-1.6, to the Unidata NetCDF Attribute Convention for Data Discovery (ACDD), to the OceanSITES convention and to the INSPIRE directive. Furthermore, it has been defined following the guidelines of the DATAMEQ working group and it fulfills the recommendations given by ROWG. To enforce semantics and interoperability, controlled vocabularies are used in the model for variable short names and standard names. All the discussions and activities for the data model definition and implementation have been carried on in strict collaboration with the US colleagues through ROWG. Other important external contributions have been given by other networks, such as the Australian ACORN network. Moreover, representatives of all these groups meet periodically at ROWG and ROW meetings, Ocean Radar Conference for Asia Pacific (ORCA) meetings and there was one ad-hoc meeting (INCREASE HFR expert workshop La Spezia 2016).

The model specifies the file format (i.e., *netCDF-4 classic model*), the global attribute scheme, the dimensions, the coordinate, data and Quality Control (QC) variables and their syntax, the QC procedures and the flagging policy for both radial and total data (Corgnati et al., 2018b). A battery of mandatory QC tests to be performed on NRT HFR data has also been defined, in order to ensure the delivery of high-quality data, to describe in a quantitative way the accuracy of the physical information and to detect suspicious or unreliable data. These QC tests standard model to be applied to HFR radial (7 tests) and total (6 tests) data were defined according to the DATAMEQ working recommendations on real-time QC and building on the QA/QC of Real-Time Oceanographic Data (QARTOD) manual produced by the United States IOOS (Corgnati et al., 2018b).

The QC standard model will be the operational standard data model starting with delivery of HFR data distribution in CMEMS-INSTAC in April 2019. Until recently, the implementation of real time QA/QC procedures of the data was depending on the HFR operator experience level. NRT validation of the HFR surface currents against surface currents of point-wise current meters or from ADCPs located inside the HFR footprint area provides a systematic data evaluation, helping also to identify periods without data (e.g., no radial velocities produced by the site, hardware/software outage, power outage, communication lost) or periods of instrument malfunction (e.g., either from the radar or from the other instruments) when velocities suddenly appear unrealistic. Of course, the

[6]http://eurogoos.eu/download/Task-Team-updates-GA2016.pdf
[7]https://www.oceanbestpractices.org
[8]https://www.oceanbestpractices.net

NRT validation should not substitute the traditional offline validation practices (performed at delayed-mode system), but it complements it. The most common delayed-mode validation of HFR currents performed so far are based on comparison with drifter trajectories and point-wise current meters and ADCPs located in the HFR footprint along with self-consistency checks at the midpoint of the overwater baseline (Lorente et al., 2014; Kalampokis et al., 2016; Corgnati et al., 2018a; Cosoli et al., 2018). Equally, a variety of validation exercises of HFR-derived wave measurements against *in situ* observations have been previously conducted (Atan et al., 2015; Gómez et al., 2015) in order to infer the accuracy of HFR remote-sensed estimations and quantify the uncertainties related to this technology.

Open Source Software Tools

One benefit of organizing the network globally are the resources that can be shared across all networks. Free and open-source software packages available for managing and analyzing HFR data have been developed. A sampling of the open source tools are described in **Table 2** including its functionality, the link to the repository and the primary authors of the tools. Constant knowledge sharing on the existing software and further updates will bring continued benefits to the global network participants. By sharing these tools as a community new features and benefits can be developed faster and more effectively than internal teams. The use of open source code should be promoted to gain full visibility and to increase reliability with the HFR worldwide community supporting the code base.

Data Access and Visualization

Within the United States, the HFR National Network data management system relies on robust communications between the individual HFR installations and centralized data repositories that are updated in NRT. Radial surface currents are measured hourly at HFR installations (a site) and synced with one of 9 local regional operations centers (a portal) that aggregate radial current data from all HFR sites within a RA. In turn, data from the portals are accumulated at two redundant data repositories (a node) which are housed at Scripps Institution of Oceanography (SIO) and the National Data Buoy Center (NDBC). The primary node, located at SIO, serves the hourly radial current files to HFRNet processing machines which produce near real-time total vector (RTV) product generated on grids with multiple resolutions (500 m, 1, 2, and 6 km). Distribution of the RTV and 25-hr average products is accomplished through a Thematic Real-time Environmental Distributed Data Services (THREDDS) server[9]. THREDDS provides an interface to data access using a number of open source protocols including OpenDap, Web Mapping Service (WMS), Web Coverage Service (WCS), NetCDF Subset, and others. Sample code is available for utilizing these services with popular data processing platforms such as MATLAB and Python/Matplotlib. Vector tiles of all RTV products are available to web mapping applications via a publicly accessible application programming interface[10].

[9]http://hfrnet-tds.ucsd.edu/thredds

[10]http://cordc.ucsd.edu/projects/mapping/api/

In addition to RTV products, the diagnostic information included in the HFR radial files is stored in a database and displayed to site operators through the HFRNet diagnostics portal. Diagnostic information includes hardware specific data such as system voltages, transmitted and reflected power and radial vector data such as range, number of solutions and signal to noise ratio.

Finally, overall IOOS network performance is evaluated using diagnostics from individual sites contributing to HFRNet through a real-time metric that is reported to the IOOS program manager and site operators. This metric categorizes when a radial file passes certain criteria, which are based on long term statistics of similar sites within the HFRNet archive. These criteria include the arrival time of a radial file (file must be received at HFRNet within 24 h of its collection) and the number of solutions (the number of valid radial solutions in the file must exceed a baseline).

In addition to THREDDS for both NRT and delayed mode (DM) products, the Australian Ocean Data Network (AODN) is making publicly available aggregated HFR data through their portal[11]. This includes surface currents, wind and wave maps. Within Europe the major platform for marine data distribution are CMEMS-INSTAC and the SeaDataNet infrastructure (SDN/SDC). They operate through a decentralized architecture based on National Oceanographic Data Centers (NODC) Production Units (PUs) organized by region for the global ocean and the six European seas and a Global Distribution Unit (DU). The core of CMEMS-INSTAC and SDC is to guarantee for the users the quality of the product delivered is equivalent wherever the data are processed.

In this framework, in order to enforce and make operational the efficient management of HFR data for INSTAC PUs, other CMEMS Thematic Centers (TAC) and Marine Forecasting Centers (MFC), the establishment of the HFR data stream has to be organized in a coordinated way, in collaboration with the regional alliances of EuroGOOS and the regional and global components of the CMEMS *In Situ* TAC. The implementation of the HFR data stream will be operated by a centralized European competence center: the EU HFR Node. This implementation will be performed in the frame of CMEMS *In Situ* TAC with the established formats and standards on QC flags and tests, dimension, naming, definition and syntax of coordinated variables.

The EU HFR Node will act as focal point with the European HFR data providers, the key EU networking infrastructures and the Global HFR network. The key roles of the EU HFR Node will be the connection with data providers for NRT and reprocessed (REP) data, the connection with CMEMS-INSTAC for NRT and REP data, the connection with SeaDataNet for REP data. The node will also ensure optimal visibility of HF radar data and foster the applications based on HF radar data. The EU HFR Node will facilitate the management and integration of any potential data provider according to a simple and very effective rule: if the data provider can set up the total surface current data flow according to the defined standards, the HFR central node only has to link

[11]https://portal.aodn.org.au/

TABLE 2 | Summary of open source software toolboxes for the processing and visualization of HFR surface current data.

Toolbox	Functionality	Programming Language	Primary Author/Link
HFR_Progs	Total currents generation, Open -boundary Modal Analysis, Interpolation and filtering, Tides, EOFs	MATLAB	Mike Cook, Naval Postgraduate School David Kaplan, Virginia Institute of Marine Science https://github.com/rowg/hfrprogs
Codar Processing	Python tools for working with radial and wave data. Loading ASCII data files, QC, exporting to NetCDF	Python Jupyter Notebook	Michael Smith, Rutgers University https://github.com/rowg/codar_processing
Hfr_gui	Graphical user interface (GUI) for processing and visualizing HFR data	MATLAB	Teresa Updyke, Old Dominion University https://github.com/rowg/hfr_gui
JRADAR	Transformation of CODAR radial and total files into the European HFR data model	Java	Jose Luis Asensio, AZTI https://github.com/llasensio/JRadar
HFR_Combiner	Standard QC processing and combination of CODAR and WERA radial current into total current and generation of radial and total data into the European HFR data model.	MATLAB	Lorenzo Corgnati and Carlo Mantovani, CNR-ISMAR https://github.com/LorenzoCorgnati/HFR_Node_tools
Total Conversion	Standard QC processing and transformation of Codar and WERA total current into the European HFR common data & metadata model	MATLAB	Lorenzo Corgnati and Carlo Mantovani, CNR-ISMAR https://github.com/LorenzoCorsnati/HFR_Node_tools
HFRadarReports	Automatic generation of monthly reports, as a new product for HFR data quality assessment	Python and La Tex	Andreas Krietmayer, Charles Troupin, Grant Rogers and Emma Reyes, SOCIB https://github.com/socib/HFRadarReports

The table shows the name of the toolbox, its main features, the programming language it was written in, the author and URL to the GitHub repository.

and include the new catalog and data stream. If the data provider cannot setup the total data generation and flow (because of lack of experience, technical capacity, etc.), the HFR Node will work on harvesting the radial data from the provider, harmonize and format these data and make them available.

For all these reasons the establishment of a centralized HFR node is the cornerstone of the operational European HFR network. The EU HFR Node became pre-operational in November 2018 and fully operational in April 2019 for CMEMS-INSTAC and SDN/SDC data delivery. It is also designed to maximize the compatibility and the possibility of mutual integration with the United States HFRNet. Links to data access portals for each of the regions are given in **Table 3**.

TABLE 3 | Website links to the portal for the global network along with links for data access in each of the three regions.

	Link to data
Global Network	http://global-hfradar.org/index.html
Region 1	http://thredds.emodnet-physics.eu/thredds/HFRADARCatalog.html
Region 2	http://hfrnet-tds.ucsd.edu/thredds/catalog.html
Region 3	https://portal.aodn.org.au/ http://www.khoa.go.kr/koofs/kor/ports/

APPLICATIONS

Search and Rescue

Public Agencies and private companies in charge of SAR missions, marine pollution response, and maritime traffic control are among the most significant targeted users of reliable surface currents. It is essential for NRT surface currents be reliable and current predictions be accurate for the specific marine SAR areas of responsibility as assigned by the IMO (International Maritime Organization).

HFR data and predictions are one important part of SAR in the United States, being used as operational input to United States Coast Guard Search and Rescue Optimal Planning System (SAROPS) since May 2009. During 2016–2017, HFR data and statistical predictions ranked 6th most popular as a source for surface current information by the United States Coast Guard and the Mid Atlantic ROMS model with HFR data assimilation reached the 4th position. HFR surface currents have been shown to reduce the search area by a factor of three in comparison with HYCOM after 96 h, presenting much higher skill score than a global model (Roarty et al., 2010).

In Europe, significant efforts are being made to promote the use of the HFR data as reliable surface current input of the SAR emergency response and environmental modeling tools in the Iberian-Biscay-Ireland seas (e.g., the ongoing CMEMS User Uptake IBISAR project) and in Malta (Gauci et al., 2016). A first coordinated approach in Mediterranean Sea on SAR applications was made during the Tosca Project (Bellomo et al., 2015), involving five HF Radar sites in different countries.

Hazard Detection

A recent advancement is the use of HFR for detection of tsunami waves. The main principle for detection is that long wave orbital velocities induced by tsunamis can be detected by the HF radar as slowly varying surface currents with characteristic space and time scales. The theory for tsunami detection by HFR was first developed in the 1970s (Barrick, 1979). However, the first detection of a tsunami by an HFR did not occur until the March 2011 Tohoku tsunami in Japan, that propagated through the Pacific Ocean (Barrick and Lipa, 2011; Dzvonkovskaya et al., 2011; Lipa et al., 2011). At that time, HF radars were not equipped with real-time detection capabilities and the occurrence of the tsunami could only be identified a posteriori by analyzing the recorded data.

Real-time HFR detection of a tsunami was accomplished by a WERA HFR system installed in Tofino, Canada (Dzvonkovskaya et al., 2017). This event occurred on October 14th, 2016, when a series of severe storms were impacting the Eastern Pacific coasts. These storms were the remnants of Typhoon Songda, thus the triggering event was atmospheric in origin and there was no seismic alert issued at that time. An in-depth a posteriori analysis of the meteorological data gathered during the event, together with the recorded HF radar data in the light of an improved tsunami detection algorithm, clearly showed that two successive abnormal long waves impacted the coast, which was a meteotsunami (Guérin et al., 2018). This tsunami was first detected by the HFR 60 km offshore, about 45 min before its arrival on the coast. The meteotsunami cleared the lowest threshold of the WERA detection software and then triggered a detection at the higher threshold 20 min later, thereby confirming the presence of the oncoming wave. The current research effort is devoted to increasing the detection range (and warning time) of such events. This can be accomplished by the combination of improved detection algorithms and increased signal-to-noise ratio of the radar signal (Grilli et al., 2017). Other meteotsunami events associated with sudden changes in surface air pressure have been detected in the Netherlands (Dzvonkovskaya et al., 2018) and the East Coast of the United States (Lipa et al., 2013). New installations in Oman and the Philippines have also been motivated by the need to protect coastlines and coastal communities from hazards such as tsunamis and storm surges. It is important to remember that the performance of these systems to detect these hazards is dependent upon continuity in electrical power during such seismic or atmospheric events and this can be a problem in remote areas. Investments to increase the resiliency of the HFR systems against power outages and other failure modes should be made by the networks.

Coastal Circulation

From long-term records, a unique view of seasonal and interannual variability in surface circulation in the coastal waters of the United States have emerged with unprecedented spatial detail, together with analysis of important differences between coastal and offshore circulation. Interannual anomalies in the NE Pacific include the 2014–2015 marine heat wave, the 2015–2016 El Niño, extreme freshwater runoff in 2017, and strong upwelling in 2009. The spatial coverage of HFR allows differentiation of features such as the upwelling jets and mesoscale eddies from wind-driven circulation over the shelf and from the large-scale California Current offshore while the temporal resolution allows resolution of the time-variation of each of these phenomena independently. Seasonal shifts in the alongshore current along the United States west coast (**Figure 12A**) characterize the upwelling season in spring-summer with persistent strong north winds, the relaxation season in autumn with weak winds, and the winter/storm season with strong southerly wind events (Garcia-Reyes and Largier, 2012). Cross-shore currents show strong seasonality at Cape Mendocino (∼40N) and other major headlands, where topography can steer the currents (e.g., deflection of the strong alongshore current) and mesoscale eddies can develop and persist (e.g., 1-year persistence of 100-km eddy off Cape Mendocino in 2008, Halle and Largier, 2011).

Along the east coast of the United States, similar long-term datasets show the distinct differences in mean and seasonal surface circulation between coastal waters and the Gulf Stream offshore. Plots of annual mean alongshelf flow show a gradual increase with distance offshore in the Mid-Atlantic Bight reaching a maximum near the shelf break (**Figure 12B**). The interannual variability of the alongshore current measured so far has a range between 3 and 11 cm/s. New insights from HFR also elucidate the eddy-driven exchange of water between coastal and offshore regions here and elsewhere (e.g., Kim et al., 2011; Rypina et al., 2016).

Over a decade of HF Radar data is also available from northern Japan, providing an unprecedented view of the distinct seasonal variation in the Soya Warm Current. Hokkaido University, has operated five HF radars along the northern coast of Hokkaido since August 2003 (Ebuchi et al., 2006). The radars cover the Soya/La Perouse Strait between Hokkaido, Japan, and Sakhalin, Russia. The Soya Warm Current enters the Sea of Okhotsk from the Sea of Japan through this strait and flows along the coast of Hokkaido as a coastal boundary current. **Figure 13** shows the monthly averaged profiles of the alongshore surface current across the eastern outlet of the Strait with respect to the distance from the coast line of Hokkaido, Japan. The error bars indicate the standard deviation over 15 years from 2003 to 2018.

Environmental Management

HF Radar data are increasingly being used in support of environmental management, including short-term pollution events and long-term resource management. Specifically, data have been used in tracking the fate of runoff (Rogowski et al., 2015) and wastewater discharges in southern California, residence time in Monterey Bay (Coulliette et al., 2007), and source-sink of water parcels off northern California (Kaplan and Largier, 2006). Further, HFR data have been used in identifying circulation features that account for plankton blooms, including harmful algal blooms imported to the Ria de Vigo (Piedracoba et al., 2016) and phytoplankton delivery to the rich ecosystems of Cordell Bank and the Gulf of

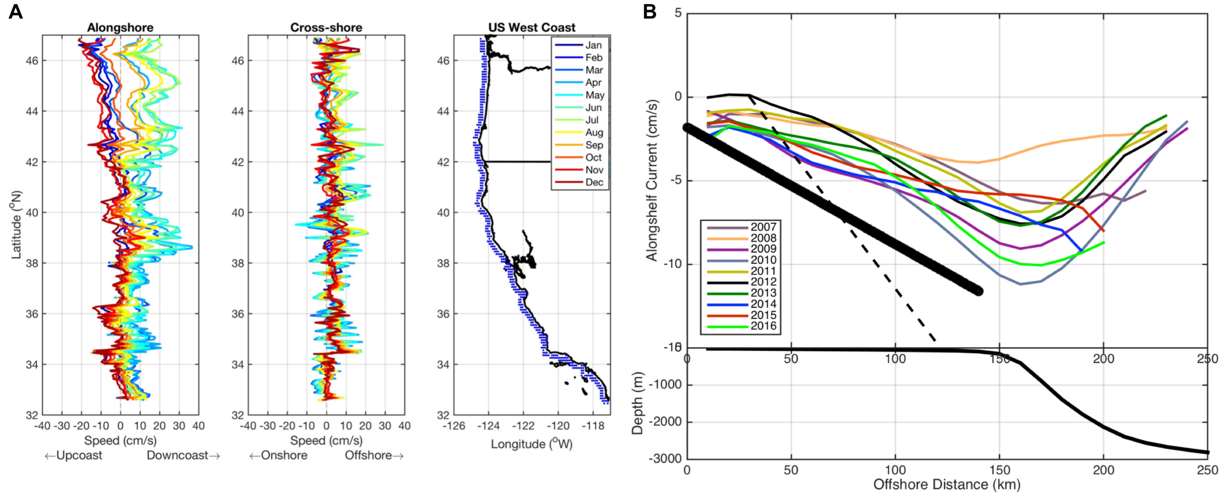

FIGURE 12 | (A) Monthly alongshore (left) and cross-shore (center) mean surface current velocities averaged from 20 km offshore along the United States West Coast (right). The raw HFR data were rotated to be parallel to the shore in 10 km segments from the Columbia River to the United States-Mexico border for each month in 2008–2017. Upcoast and onshore flows are negative whereas downcoast and offshore flows are positive. **(B)** Yearly alongshelf currents within the Mid Atlantic Bight of the United States East Coast from 2007 to 2016. The depth averaged alongshelf flow from Lentz model (2008) is given as the solid black line while the regression of past current meter deployments is represented by the dashed black line. Water depth (m) along the cross section is plotted below the figure.

Farallones (Halle and Largier, 2011). Other unpublished work has used these surface current data in designing networks for marine protected areas, and assessment of transport of juvenile salmonids in coastal waters. Off the west coast of the United States, HFR data are also an important component of an index of the condition of the environment for ecosystem health (Sydeman et al., 2013), been used in fishery oceanography (Nishimoto and Washburn, 2002; Bjorkstedt et al., 2010) and a recent analysis has used these data to explain anomalous and unprecedented appearance of southern species during the 2014–2015 marine heat wave (Sanford et al., 2019). These are just some examples that use HFR data to address environmental questions and inform management agencies addressing water quality, marine resources, and marine conservation.

Ocean Model Validation and Assimilation

In addition to direct use of HFR data in operational and retrospective assessment, HFR surface current data are distributed to various research and development groups that assimilate HFR-derived surface current into numerical models that simulate 3-dimensional circulation and water properties in the coastal ocean. Because of the large spatial extent and high-frequency sampling of surface currents that resolve tidal variability and small-scale topographic effects, the assimilation of these data has been shown to greatly improve model realism and confidence (e.g., Chao et al., 2018). Increasingly, this is a preferred way to deliver the value of HFR datasets as it combines the benefits of models and real data. A number of publications already exist on the assimilation of both surface currents and wave HFR data (Breivik and Sætra, 2001; Paduan and Shulman, 2004; Barth et al., 2008, 2011; Waters et al., 2013; Marmain et al., 2014; Ren et al., 2015; Sperrevik et al., 2015; Stanev et al., 2015; Iermano et al., 2016; Hernández et al., 2017, to mention only a few examples). For the entire United States west coast, the large-scale, high-resolution West Coast Ocean Forecast System (WCOFS) is developing a capability to assimilate HFR surface currents into a 2-km-resolution, Regional Ocean Modeling System (ROMS) numerical model (Kurapov et al., 2017). Typically, radial data are used for assimilation into regional models. An effort is underway led by University of California Santa Cruz in evaluating the impact of ocean observing system measurements on ocean analysis and forecast systems – including assessment of the best data type and the best data locations in terms of improved model realism and confidence. The project is focused on advancing ROMS (Wilkin and Hunter, 2013) through use of 4-dimensional variational data assimilation diagnostic tools to assess the impact of observations on analysis and forecasts. Indeed, the combined assimilation of the data with satellite altimetry and multi-platform observations improve both the representation of small-scale features and the understanding of the impact of coastal processes on larger scales.

While data assimilation is an exciting recent development in the use of HFR data and in realizing and delivering its value, HFR data have long been used as a very valuable data set for evaluating high-resolution numerical simulations of coastal circulation. Compared with other multi-platform observations (e.g., gliders, fixed moorings, Lagrangian drifters), HFR data are preferred as the network provides routine data at high spatio-temporal resolution comparable with the models. This cross-validation has provided an unprecedented opportunity for model assessment and contributed valuable insights into the small-scale variability of coastal ocean currents. The comparison of the mean velocity fields between model and HFR surface currents detected circulation biases in coastal models at a scale that is not properly resolved by altimetry (Mourre et al., 2018). Operationally, HFRs are increasingly considered part of core validation systems (Lorente et al., 2016; Aguiar et al., 2018) and tools like the North Atlantic Regional Validation (NARVAL), the

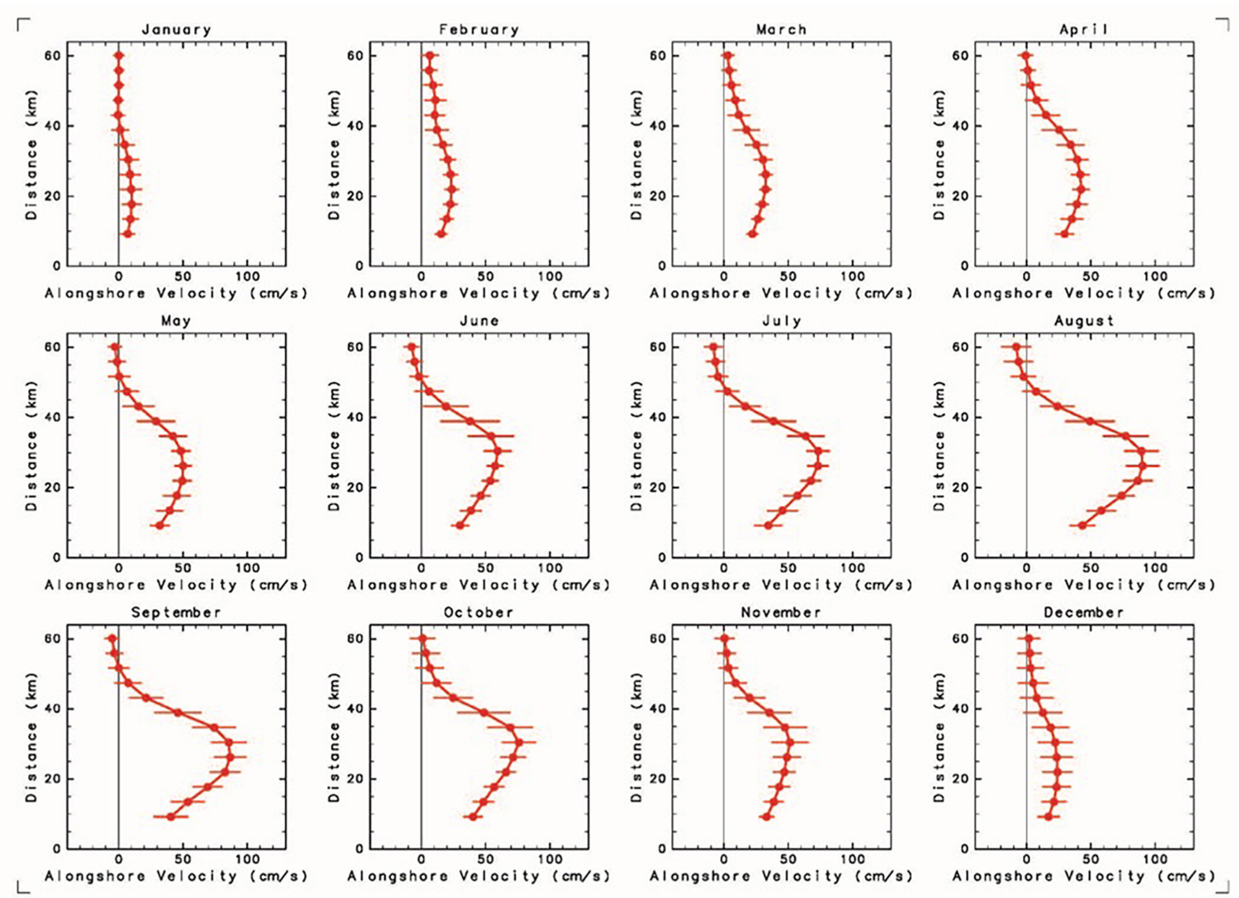

FIGURE 13 | Monthly averaged profiles of the alongshore surface current velocity component across the eastern outlet of the Soya/La Perouse Strait with respect to the distance from the coast line of Hokkaido, Japan. The error bars indicate the standard deviation over 15 years from 2003 to 2018.

IBI-MFC forecast system validation web tool (Sotillo et al., 2015) or the SOCIB- WMOP Operational Validation System (Juza et al., 2016) are used to systematically assess model outputs at different time scales. Complementarily, HFR systems play a primary role in multi-model comparison in overlapping regions since they help in judging the strengths and weaknesses of each forecasting system in the modeling of key ocean processes and also to deepen the understanding of discrepancies in model predictions. With CMEMS regional models special emphasis has been placed on the use of HFR measurements in the intercomparison of regional models against nested coastal model solutions in order to elucidate the added value of dynamical downscaling approaches (Hernandez et al., 2018).

GAPS AND FUTURE CHALLENGES

High frequency radar technology for surface current mapping has been widely implemented in the last two decades, with a remarkable growth in applications in the last decade. In the context of the S-curve of technology development, HFR networks are in their middle age with the rapid development of new insights, applications and benefits. Globally, HFR systems are and have been operated in 25% of the countries with an ocean coastline. The Global HF Radar Network will work to develop HFR capabilities in new countries and continue its mission to increase the number of coastal radars operating around the globe by maintaining a dialogue with organizations like the Group on Earth Observations (GEO), Intergovernmental Oceanographic Commission (IOC), Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), and Partnership for Observation of the Global Ocean (POGO).

High frequency radar has proven operational value that is also well recognized through inclusion in operational protocols in the United States and elsewhere. Value is recognized specifically in rapid-response (e.g., search and rescue; oil spill) and also more recently in hazard identification and warning (e.g., tsunami). Data are used directly as well as ingested by models with operational capabilities. Further, HFR time series comprised of hourly maps of surface currents have been sustained for 10–20 years in several locations, demonstrating the value of HFR networks for retrospective assessment of environmental change, including seasonal and interannual fluctuations in coastal circulation and ecosystems. The Global Network has just begun conversations on developing the infrastructure to curate and serve these long data records. At the EU level, and following the recommendation given by the United States colleagues, best practices of operations and maintenance of the HFR sites are currently being developed. The development of troubleshooting guides, helping to minimize site downtime and the implementation of aids to operations and managements as well as the creation of EU technical steering teams, that could be related with the best practices working group advisor committee as expert panels are being considered in the framework of different joint proposals.

High frequency radar technology is a form of remote sensing that offers a relatively low-cost method for tracking coastal waters with both operational and environmental dividends. However, beyond the initial investment, a sustained commitment to operational up-time and data quality is essential to realize these dividends. This review of the current status of the HFR global network highlights the major challenges for data production and applications that can be addressed at a global level to properly inform choices to direct the future evolution of HFR networks as coastal ocean observing platforms. In terms of applications, further efforts are needed in the development of novel signal processing methodologies for allowing the operational delivery of other information (e.g., waves and wind maps) as well as to exploit synergy between HFR and other multi-platform observing systems (e.g., satellite, gliders, drifters). Secondly, the use of HFR surface-velocity fields for improving operational high-resolution forecast models through data assimilation is emerging strongly. Nevertheless, use of the surface current measurements to improve the model downward through the water column represents an additional challenge (Paduan and Washburn, 2013), as well as the combined assimilation of HFR data with satellite altimetry and multi-platform observations. Progress in this research will offer a unique opportunity to increase the understanding of small-scale features and their interaction with larger scale processes and feedback mechanisms. Simultaneously, the progress in observation and forecasting in the coastal ocean will allow us to develop new science-based products of high added value, enhancing the HFR data discovery and the visibility of the HFR work and applications. The development of more user-driven products will help to reinforce the HFR user's loyalty and to attract new communities, beyond academic and SAR agencies (e.g., environmental monitoring).

In terms of data production, a key overarching concern for the network is continued development of the HFR technology, sufficient supply of experienced HFR technicians and scientists and effective management of the frequency spectrum through national coordinating bodies which should hopefully limit the instances of radio frequency interference. HFR site sustainability has emerged as a challenge in those countries (e.g., Canada) where the HFR sites are owned and operated by universities in the context of finite research programs, and also in regions where HFR sites have been operated for a long time and confronted by "aging infrastructure" without renewal of hardware. One of the top priority issues is the maintenance of continued financial support to preserve the infrastructure and core service already implemented, but also funding to extend the networks at diverse national scales for an overall spatial coverage. The need for data standardization, harmonization and integration has also emerged. The future integration of the HFR data from the MARACOOS network into CMEMS-INSTAC in April 2020 (tentative date) could be considered the first step toward this goal.

An active global HFR network is crucial for pushing forward HFR scientific developments, promoting training activities, encouraging the integration of the HFRs into operational maritime monitoring and environmental assessment, and boosting networking toward an integrated, evolving and sustained HFR global network over the next decade.

AUTHOR CONTRIBUTIONS

HR, TC, PL, ER, SC, JL, and LW contributed to the main structure and content of all sections. LH contributed to Abstract, **Figure 1** and **Table 1**, and made substantial contributions to the Introduction and Development of Networks sections. EAF and PL contributed to the European Network and Ocean Model Validation and Assimilation sections. LC, CM, AG, JM, and AR contributed to the European Network, Deployment and Maintenance Best Practices, Quality Assurance/Quality Control, and Data Access and Visualization sections. ER made substantial contributions to the writing and revising of the manuscript, particularly at the Deployment and Maintenance Best Practices, Search and Rescue, Ocean Model Validation and Assimilation, and Gaps and Future Challenges sections. LW contributed to Introduction, Europe, Africa and Middle East (Region 1), and Hazard Detection sections. JS contributed to the description of HFR in Morocco, Saudi Arabia, and Portugal, and **Figure 7**. BW and KB contributed to the description of HFR in Canada. BH contributed to the description of HFR in Chile. XF-V and KS-M contributed to the description of HFR in Mexico and **Figure 8**. TC contributed to the description of HFR in United States. SC contributed to the description of HFR network, data uptake, and QC in Australia. PR contributed to the description of HFR in Vietnam and **Figure 10**. S-HL contributed to the description of HFR in Korea and **Figure 11**. SP contributed to the description of HFR in Thailand. J-WL contributed to the description of HFR in Taiwan. HR contributed to **Figures 2–4**, **6**, **12B**, and **Table 3**. TC and LH contributed to **Figures 5A**, **9**. AR and JM contributed to **Figure 5B**. DG contributed to **Figure 12A**. NE contributed to **Figure 13**. ER and HR contributed to **Table 2**. C-AG and SG contributed to the Hazard Detection section. JH, ET, MO, and SG contributed to the content of all sections.

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frontiers in Marine Science

REVIEW
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The U.S. Integrated Ocean Observing System: Governance Milestones and Lessons From Two Decades of Growth

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Reflecting on two decades of the U.S. Integrated Ocean Observing System (IOOS) is particularly timely during the OceanObs'19 meeting. Over the past twenty years since the first OceanObs meeting was convened, U.S. IOOS has advanced from regional proofs of concept to a national, sustained enterprise. U.S. IOOS has grown to include 17 Federal partners and 11 Regional Associations (RAs) that implement regional observing systems covering all U.S. coasts and Great Lakes with activities spanning from head of tide to the U.S. exclusive economic zone (EEZ). The National Oceanographic and Atmospheric Administration (NOAA), as lead agency, provides guidance and national-level coordination. An interagency body, the Integrated Ocean Observation Committee (IOOC), communicates across federal agencies and ensures IOOS maintains strong connections to the Global Ocean Observing System (GOOS). Additionally, a federal advisory committee, non-federal association, and various informal partnerships further inform and advance the IOOS enterprise. This governance structure fosters both national consistency, regional flexibility, and global contributions addressing the diverse needs of U.S. coastal and Great Lakes stakeholders.

Keywords: U.S. IOOS, regional association, observation, integrated, governance, ocean, CARICOOS, SECOORA

INTRODUCTION: TWO DECADES OF U.S. IOOS

Over the past 20 years since the first OceanObs meeting was convened, the U.S. Integrated Ocean Observing System (IOOS[1]) has advanced from regional proofs of concept to a national, sustained enterprise. A review of the evolution and continued planning for IOOS governance provides one example of how a national system may operate. This governance structure fosters national consistency, regional flexibility, and global contributions addressing the diverse needs of U.S. coastal and Great Lakes stakeholders.

[1] https://ioos.noaa.gov/

Early History and Origins: 1999–2008

Common among most oceanographic enterprises, present-day IOOS traces its history back to the U.S. Department of Defense. During World War II and the Cold War that followed, the U.S. Navy invested in oceanographic observations and research to support marine weather forecasting and anti-submarine warfare. The U.S. civil science community focused on collection of ocean data from space, ships, and buoys to support oceanographic research, weather forecasting, and maritime operations. During the late 1990's, several international scientific organizations, with strong leadership from the U.S. ocean research community, collaborated to develop a plan to increase understanding of the oceans for both research and broader societal needs. From these efforts, the Global Ocean Observing System (GOOS) was born. **Table 1** summarizes key events that led to the U.S. Integrated Ocean Observing System.

During this same time period, the National Ocean Research Leadership Council (NORLC), a statutory committee consisting of 15 federal agencies involved in conducting, funding or using ocean research and its applications, convened a Task Team of Federal Government and academic ocean experts to address the needs of the nation for sustained ocean observing. The report, *Toward a U.S. Plan for an Integrated, Sustained Ocean Observing System,* (Ocean Observations Task Team, 1999) identified seven areas of societal benefit to be the drivers for the design and implementation of a U.S. IOOS program. These seven drivers are still used as guidance today.

IOOS Societal Benefit Areas:

1. Detecting and forecasting oceanic components of climate variability.
2. Facilitating safe and efficient marine operations.
3. Ensuring national security.
4. Managing living resources for sustainable use.
5. Preserving healthy and restoring degraded marine ecosystems.
6. Mitigating natural hazards.
7. Ensuring public health.

Following the recommendations from the NORLC task team, an interagency program office was established in 2000. This program office, Ocean.US, operated through interagency funds from U.S. agencies leading the way for a more coordinated ocean observing system. For the following 8 years, Ocean.US led the planning for and implementation of a sustained IOOS. This effort included hosting a pivotal community workshop and development of a subsequent, sentinel report, *Building Consensus: Toward an Integrated and Sustained Ocean Observing System (IOOS)* (Ocean US, 2002). Broad community consensus was achieved in a number of important areas and established the strategic framework for what would become IOOS.

Today, most of the original system design structure, components, and governance remains, attesting to the robust buy-in and legitimacy of the initial design. The report established IOOS as a system encompassing both open-ocean and coastal observing activities. Regional institutions would be formed to organize efforts in coastal areas, and coordination among regional groups would be facilitated by a national association. Perhaps most notably, IOOS would be a distributed system of linked elements: an observing subsystem consisting of platforms, sensors, and instrumentation; a data management and communications subsystem consisting of the data infrastructure to improve data standardization, protocols, and quality assurance and control; and an analysis, modeling and applications subsystem to promote data assimilation and synthesis and the development of predictions, products, and tools to support end-users.

The seven areas of societal benefit were endorsed as drivers for IOOS during the Airlie House meeting, the first community workshop. The workshop also identified 20 high-priority core ocean observation variables necessary to meet the seven societal goals. This list of variables was codified in the U.S. IOOS Development Plan, the International Global Ocean Observing System Coastal Theme Report and the GOOS Coastal Module Implementation. Additional variables have since been added with broad community support, bringing the current total to 34. The community consensus built through this workshop and the ensuing formal and informal engagements were critical to the current success of the IOOS enterprise.

IOOS Core Variables

The IOOS core variables and groups of variables are defined as those required to detect and predict changes in the oceans, coasts, and Great Lakes. These include 20 variables that were identified at the Airlie House meeting and an additional six that were included prior to the IOOS Summit (Interagency Ocean Observing Committee and NASA, 2014), and additional variables added by the Interagency Ocean Observation Committee (IOOC) Biological Integration and Observation Task Team (National Ocean Council, 2016). They are in general alignment with current GOOS Essential Ocean Variables (EOVs) (UNESCO, 2012), and include:

Physics: bathymetry, bottom character, currents, heat flux, ice distribution, salinity, sea level, surface waves, stream flow, temperature, wind speed, and direction;

Biogeochemistry: acidity (pH), colored dissolved organic matter, contaminants, dissolved nutrients, dissolved oxygen, ocean color, optical properties, partial pressure of CO_2, total suspended matter;

Biology & Ecosystems: pathogens, biological vital rates, coral species and abundance, fish species and abundance, invertebrate species and abundance, marine mammal species, and abundance, microbial species abundance and activity, phytoplankton species and abundance, sea birds species and abundance, sea turtles species and abundance, submerged aquatic vegetation species, and abundance, zooplankton species and abundance, nekton diet, and sound.

Regional Structure

Ocean.US also recognized the need for regional leadership to sustain coastal ocean observations and in 2003 sponsored a summit to address the structure and functions of regional coordination. As a result, the Regional Associations (RAs) were recognized as a part of the core IOOS governance. In 2003 the National Federation of Regional Associations (now the

TABLE 1 | Milestones of U.S. ocean observation governance.

September 1996	Defense Authorization Act (PL 104-201) established the National Ocean Partnership Program (NOPP), under the National Ocean Research Leadership Council (NORLC)
April 1998	U.S. Global Ocean Observing System (GOOS) steering team formed
October 1999	International Global Ocean Observing System meeting Ocean Obs'99 defines requirements, coordination and recommendations
November 1999	Gulf of Maine Ocean Observing System, the first regional system, incorporated.
May 2000	Ocean.US, an interagency planning body, established under the NORLC
March 2002	Airlie House Workshop hosted by Ocean.US
September 2004	U.S. Ocean Commission recommended a U.S. Integrated Ocean Observing System (IOOS)
December 2006	NOAA established the U.S. IOOS Program
February 2008	National Federation of Regional Associations (NFRA) established
March 2009	Integrated Coastal Ocean Observation System (ICOOS) Act: Established the Interagency Ocean Observation Committee (IOOC); Designated NOAA as lead Federal agency; Included "all relevant non-classified civilian coast and ocean Observations"
November 2009	International Global Ocean Observing System revised requirements and recommendations at OceanObs '09 in Venice, Italy
July 2010	Executive Order #13547 established National Ocean Council (NOC); IOOC reports to Deputy-Level of the NOC
June 2012	Framework for Ocean Observations published
November 2012	National Federation of Regional Associations (NFRA) changed its name to the IOOS Association (IA)
November 2012	IOOS Summit held in Herndon, VA near Washington, DC
December 2016	Published first IOOS enterprise study, "The Ocean Enterprise: A Study of U.S. Business Activity in Ocean Measurement, Observation, and Forecasting"
September 2018	All IOOS RAs certified as Regional Information Coordinating Entities
October 2018	IOOS receives Congressional approval for reorganization within NOAA from staff office to formal office in the National Ocean Service

IOOS Association[2], a non-profit organization, was formed to coordinate activities among the RAs, facilitate collaboration with the federal agencies, and to champion the needs for ocean observing.

IOOS first started as a series of regional programs that received dedicated Congressional funding. These initial regional observing efforts formed the basis for the national network of regional systems. In 2007, after work done by the ocean community, agencies, and the regional systems, the U.S. National Oceanic and Atmospheric Administration (NOAA) created two budget lines for IOOS, one for the national program housed in NOAA and one for regional systems. This allowed the functions performed by Ocean.US to transition to the IOOS program within NOAA's National Ocean Service. NOAA awarded funding to newly formed, regionally led Regional Associations through a competitive, peer-reviewed process for the first time in fiscal year 2007. NOAA continues to provide leadership, management, and oversight to ensure IOOS regional activities are consistent with national IOOS data management standards and infrastructure.

FORMAL MANDATE TO IMPLEMENTATION: 2009—PRESENT

The Integrated Coastal and Ocean Observation System (ICOOS) Act of 2009 authorized the established framework of IOOS and designated NOAA as the Federal agency lead, citing the U.S. IOOS Development Plan as the central guiding document. The ICOOS Act also established the Interagency Ocean Observation Committee (IOOC) to manage budgeting, standards, and protocols and coordinate the activities for the 17 IOOS Federal agencies. In addition, the Act established voluntary certification standards for the Regional Associations that design and operate the regional observing systems and created a Federal Advisory Committee to provide insight and advice to the IOOC and the NOAA Administrator.

Core Capabilities of the IOOS Enterprise

With the enactment of the ICOOS Act of 2009, the community recognized the need for coordination and stewardship of IOOS development and sustainment that enables distributed national and regional IOOS implementation. The U.S. IOOS Blueprint (USIOOS Program, 2010) (the Blueprint) was written to define IOOS requirements and to enable a full costing analysis of all IOOS components.

The Blueprint identified, described, and organized the specific functional activities to be developed and executed by IOOS partners and coordinated by the U.S. IOOS program, in accordance with the provisions of the ICOOS Act of 2009 and previous IOOS developmental guidance. The Blueprint also described specific activities and tasks that the U.S. IOOS program coordinates with partners to develop, deploy, and sustain those functional activities that make up a fully capable IOOS.

While parts of the Blueprint have evolved as the IOOS enterprise has matured over the past decade, the Blueprint provided the basis for other critical analyses. Based on the Blueprint architecture and supporting documentation from the U.S. IOOS program, 11 Regional Associations, and several partner Federal agencies, an independent cost estimate for IOOS was produced. The Blueprint also provided a basis for the IOOS Programmatic Environmental Assessment

[2] http://www.ioosassociation.org/

(PEA) to identify potential impacts on the environment, develop alternatives and tactical plans to mitigate identified impacts, and build a strategy to address dynamic situations at a tiered level when necessary. As the IOOS enterprise matures and authorizes an increasing number of activities by non-federal partners, it is imperative to analyze the impact on the human and natural environment. This PEA also provides an efficient process for systematically analyzing IOOS compliance with applicable environmental laws and regulations.

The preceding events, while not exhaustive, were key moments in shaping IOOS into its current governance structure. The diversity of the IOOS community—federal, non-federal, geographically and sectorally inclusive—drives this nationally coordinated, regionally flexible, and globally relevant enterprise. **Table 1** summarizes key events that led to the U.S. Integrated Ocean Observing System.

PRESENT NATIONAL AND GLOBAL GOVERNANCE

The IOOS of today is a national-regional partnership working to provide integrated ocean, coastal, and Great Lakes information. The IOOS Enterprise provides new levels of public access to observations, data integration from disparate federal and non-federal sources, and new decision support tools for Federal, State, local, tribal, and private sector decision makers to protect lives and property. Easier and better access to this information is improving our ability to understand and predict coastal events—such as storms, wave heights, and sea level change. This information is critical to prepare for and manage risks to commerce and communities, make effective decisions in the public and private sectors, and support the nation's economy.

As referenced in **Table 1**, on March 30, 2009, President Obama signed into law the Integrated Coastal and Ocean Observation System (ICOOS) Act of 2009 (P.L. 111-11, Title XII, Subtitle C), with the following overarching purposes:

- "Establish a national integrated System of ocean, coastal, and Great Lakes observing systems comprised of federal and non-federal components ..." "... designed to address regional and national needs for ocean information, to gather specific data on key coastal, ocean, and Great Lakes variables, and to ensure timely and sustained dissemination and availability of these data" to support national defense, marine commerce, navigation safety, weather, climate, and marine forecasting, energy siting and production, economic development, ecosystem-based marine, coastal, and Great Lakes resource management, public safety, and public outreach training and education;"
- "improve the Nation's capability to measure, track, explain, and predict events related directly and indirectly to weather and climate change, natural climate variability ..." and
- "authorize activities to promote basic and applied research to develop, test and deploy innovations and improvements ..."

National Governance[3]

IOOS is comprised of 17 federal agencies, 11 Regional Associations (RAs), and a technology verification and validation organization [the Alliance for Coastal Technologies (ACT)]. NOAA serves as the lead federal agency and houses the IOOS program. Additional partners include a large and growing number of organizations from industry, academia, state, local, and tribal governments, and other federal and non-federal organizations.

All 17 federal agencies contribute to the mission of IOOS. These federal agencies include the National Oceanic and Atmospheric Administration (NOAA); the National Aeronautics and Space Administration (NASA); the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEM and BSEE); the Office of Naval Research (ONR); the U.S. Army Corps of Engineers (USACE); the U.S. Geological Survey (USGS); the Department of Energy (DOE); the Department of Transportation (DOT); the U.S. Arctic Research Commission (USARC); the National Science Foundation (NSF); the Environmental Protection Agency (EPA); the Marine Mammal Commission (MMC); the Oceanographer of the Navy, representing the Joint Chiefs of Staff (JCS); the U.S. Coast Guard (USCG); the Department of Agriculture, Cooperative State Research, Education, and Extension Service (CSREES); the Department of State (DOS); and the Food and Drug Administration (FDA). These federal agencies are generally responsible for global and national scales of observation and analysis, and provide active support, funding, guidance, or advice to the program. The federal partners form the ICOOS Act-mandated Interagency Ocean Observation Committee (IOOC), and they play a direct oversight role in the development of IOOS. Many of these federal agencies also are part of the Global Ocean Observing System (GOOS) that provides a framework for international cooperation on observations, modeling and analyses of the interconnected nature of the world's oceans. The U.S. IOOS program resides within NOAA as lead Federal agency and is supported and staffed by NOAA and to the extent possible supports other agency details (US Army Corps of Engineers and Marine Mammal Commission to date) to achieve its interagency mission.

NOAA

NOAA has long had a strong federal presence in ocean observing both in the U.S. and globally. With the passing of the ICOOS Act, NOAA was formally named lead federal agency for implementing IOOS for the nation. The U.S. IOOS program receives annual appropriations through NOAA's budget, and relies on NOAA's federal infrastructure to support administrative functions and allow the IOOS program to meet its broader mission. Through NOAA appropriations, IOOS funds the Regional Associations via 5-year competitive, cooperative agreements. The U.S. IOOS program partners with other NOAA programs and offices with ocean observing components.

[3]https://ioos.noaa.gov/about/governance-and-management/

U.S. IOOS Program

The U.S. IOOS program is organized into two divisions that implement policies, protocols, and standards to sustain and advance IOOS and oversee the daily operations and coordination of the System: (1) Operations Division (Ops) and (2) Regions, Budget, and Policy (RB&P).

The Operations Division coordinates the contributions of Federally-owned observing and modeling systems and develops and integrates non-federal observing and modeling capacity into the system in partnership with IOOS regions. This division serves as the system architect for data processing, management and communications in accordance with national and international standards and protocols and leads nationwide program integration for modeling development, undersea glider operations, high frequency radar, biology, and animal telemetry. More details follow on IOOS national data management governance.

The Regions, Budget, and Policy Division oversees functions including management, budgeting, execution, policy, and regional and external affairs to further the advancement of IOOS. This division works to secure resources that help build the IOOS structure and support ICOOS Act implementation in support of NOAA and other federal agency missions. Additionally, RB&P initiates and maintains relationships to encourage participation in IOOS by federal agencies, non-federal groups and industries.

National Data Management Governance

The IOOS Data Management and Communication (DMAC) subsystem is the primary mechanism for data integration required for IOOS to function effectively. Core capacities for contributing data to IOOS are described on the IOOS website[4] and include open data sharing, data management planning and coordination, provision of data to the Global Telecommunication System, data access services, catalog registration, common data formats, metadata standards, storage and archiving, ontologies/vocabularies/common identifiers, and consideration for long-term operations. Data sources are determined for integration based on user requirements, policy, and standards at the national and regional levels. Standards must work across a range of geographic scales: regional, national, and global to be incorporated as a IOOS best practice. The national DMAC effort guides IOOS partners in developing and implementing effective best management practices and community-adopted standards. This paper does not focus on the many advances made in data management as IOOS has evolved.

Interagency Ocean Observation Committee

The Interagency Ocean Observation Committee (IOOC) was created by the ICOOS Act of 2009 and oversees efforts to develop IOOS. Led by three federal Co-Chairs and supported by agency representatives and support staff, the Committee carries out various provisions of the Act for implementing procedural, technical, and scientific requirements to ensure full execution of the System. For example, the IOOC formally adopted the standards for certifying the RAs. The IOOC has been particularly effective in advancing IOOS priorities through establishing task teams to address specific projects or challenges. Through establishing an IOOC task team to review ocean biological variables, the IOOS community came to consensus on additional biological variables the IOOS enterprise should plan to integrate into the system. Interagency collaboration is essential to achieve ocean science and technology priorities and, in particular, for planning and coordination of the System.

IOOS Advisory Committee

IOOS Advisory Committee is a statutory Federal Advisory Committee established in the ICOOS Act. First convened in 2012, this committee provides non-federal subject matter expert recommendations from the ocean observing community to both the NOAA Administrator and the IOOC. Its recommendations are used to inform strategic planning within NOAA and among the federal agencies of the IOOC, including how to best sustain and advance the entire IOOS enterprise. Establishing this committee provides a formal mechanism for expert non-federal advice on IOOS.

Global Governance

IOOS governance is not only integrated with the global ocean observing community, it shares a direct history with GOOS. GOOS was initiated in the early 1990s with the objective of designing and implementing an ongoing, multidisciplinary observing system focused on the production and delivery of data and products to a wide variety of users. Specifically, GOOS was designed to monitor, understand and predict weather and climate; describe and forecast the state of the ocean, including living resources; improve management of marine and coastal ecosystems and resources; mitigate damage from natural hazards and pollution; protect life and property on coasts and at sea; and enable scientific research. Early planning for integrated U.S. ocean observations came directly from planning and research done by the global ocean community. GOOS is implemented by member states via their government agencies, navies and oceanographic research institutions working together in a wide range of thematic panels and regional alliances.

In the early 2000s, GOOS established policies to guide the development of GOOS Regional Alliances (GRAs), generally multinational bodies that focus on sustained ocean observations and the associated development of product and services. GRAs were introduced to integrate national needs into multinational regional systems and to deliver the benefits of GOOS strategy, structure, and programs at a regional and national level, and secondarily at a global level. GRAs are formed to implement activities that require multinational coordination to meet national priorities for detecting and predicting changes in coastal marine environments and resources.

GRAs are coalitions of nations and/or institutions, which share GOOS principles and goals, but are mostly concerned with local priorities and organized around regional seas or coastal environments. Thirteen GRAs represent different regions of the globe, emphasizing regional priorities, differing by need, resources and culture. Some GRAs emphasize data sharing or

[4]https://ioos.noaa.gov/data/contribute-data/

regional capacity development, while others are building out extensive observation systems with dedicated marine service goals, such as oil spill response capabilities or typhoon forecasting. The IOOS GOOS Regional Alliance is the formal GOOS Intergovernmental Oceanographic Commission (IOC) interface to IOOS.

IOOS Regional Associations

Geographic Approach

Like GOOS, IOOS employs a regional approach to observing to address the large and diverse ecosystems of the U.S. IOOS includes the cold waters of the Arctic, the warm, tropical waters of the Caribbean and the fresh, drinkable waters of the Great Lakes. Each of the 11 IOOS regions has unique physical, geographic, chemical and biological characteristics and human uses and needs. The diversity of the ecosystems, the large geographic areas and the different needs of users call for a regional approach to coastal observing. The IOOS network of 11 Regional Associations (RAs) provides services to the entire coastline of the U.S., including the islands, territories and the Great Lakes. The 11 RAs, as seen in **Figure 1**, include: Alaska Ocean Observing System (AOOS), Caribbean Coastal Ocean Observing System (CARICOOS), Gulf of Mexico Coastal Ocean Observing System (GCOOS), Great Lakes Observing System (GLOS), Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS), Northwest Association of Networked Ocean Observing Systems (NANOOS), Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS), Pacific Islands Ocean Observing System (PacIOOS), Southern California Coastal Ocean Observing System (SCCOOS) and Southeast Coastal Ocean Observing Regional Association (SECOORA).

Federal to Regional Structure

The IOOS enterprise that links together 17 federal agencies with 11 RAs is unique. The RAs complement the federal system by providing:

- Higher resolution observations that complement federal infrastructure,
- A trusted source of information that is responsive to regional needs,
- Regional forums for regional experts, government agencies, industry and users to coordinate efforts, leverage assets and maximize limited resources,
- Tailored products that are specific to the unique characteristics of the region,
- Data portals that integrate and make readily accessible data from multiple sources, and
- Testbeds for developing new technologies and approaches in partnership with industry, federal entities and regional stakeholders and experts.

Stakeholder engagement is key to the work of the RAs and fundamental to the design and delivery of the regional systems and information products. From the start, IOOS engaged users and regional data providers to identify needs, set priorities, leverage existing assets, fill gaps and deliver useful information. Each region tailors the design of platforms and sensors, models, and data management plans based on existing infrastructure, priorities of users, and available resources.

RA Certification

In 2018, IOOS celebrated a major milestone when all 11 RAs were certified as Regional Information Coordinating Entities under the provisions outlined in the ICOOS Act. To be certified under this voluntary program, a RA had to meet standards for management and governance and for data management. The governance criteria require the regions to demonstrate they have a structure that is open and transparent, responsive to the needs of the region and promotes a stable and long-lasting organization. The data management criteria require adherence to rigorous standards for collection, quality control, and long-term archiving. The U.S. IOOS program is responsible for review and certification, which lasts for 5 years at which point a RA can reapply. Users benefit from this certification process by knowing they can rely on the data and information tools offered by the RAs to be as reliable and trusted as the data from federal sources such as NOAA. Scientists, managers, and businesses are able to use this information without spending additional time to quality check or archive the data. Certification also provides liability protection for the RAs.

The governance standards for certification set high-level criteria that allow each region to design systems that work best for their circumstances. For example, about half of the RAs are formally recognized as non-profit organizations, as defined by section 501(c)(3) of the U.S. Internal Revenue Service code while the others are established by a memorandum of agreement. Each RA is governed by a set of by-laws that outlines how the organization makes decisions, selects leaders and their terms of office, the process by which institutions and others can become members, liability and provisions for how assets should be handled if the organization dissolves.

RA Membership Structure

RA membership structure varies from region to region. Membership in all regions is diverse and represents the broad interests in coastal data and information including governmental agencies (federal, tribal, state and local), research institutions, industry, non-governmental organizations and stakeholders. Members benefit from being a part of the RA by having a seat at the table while decisions are made and participating in a forum for discussing shared issues, and by supporting sustained operational observing efforts. About half of the RAs require membership dues, which can range from $10 for individuals, such as fishermen and recreational users, to $10,000 for large organizations. The maximum amount of funding raised by any single RA annually is approximately $40,000. These dues provide a flexible source of funds that can be dedicated to activities such as advocacy. Other RAs maintain an open membership process that requires signing a memorandum of agreement without a financial commitment.

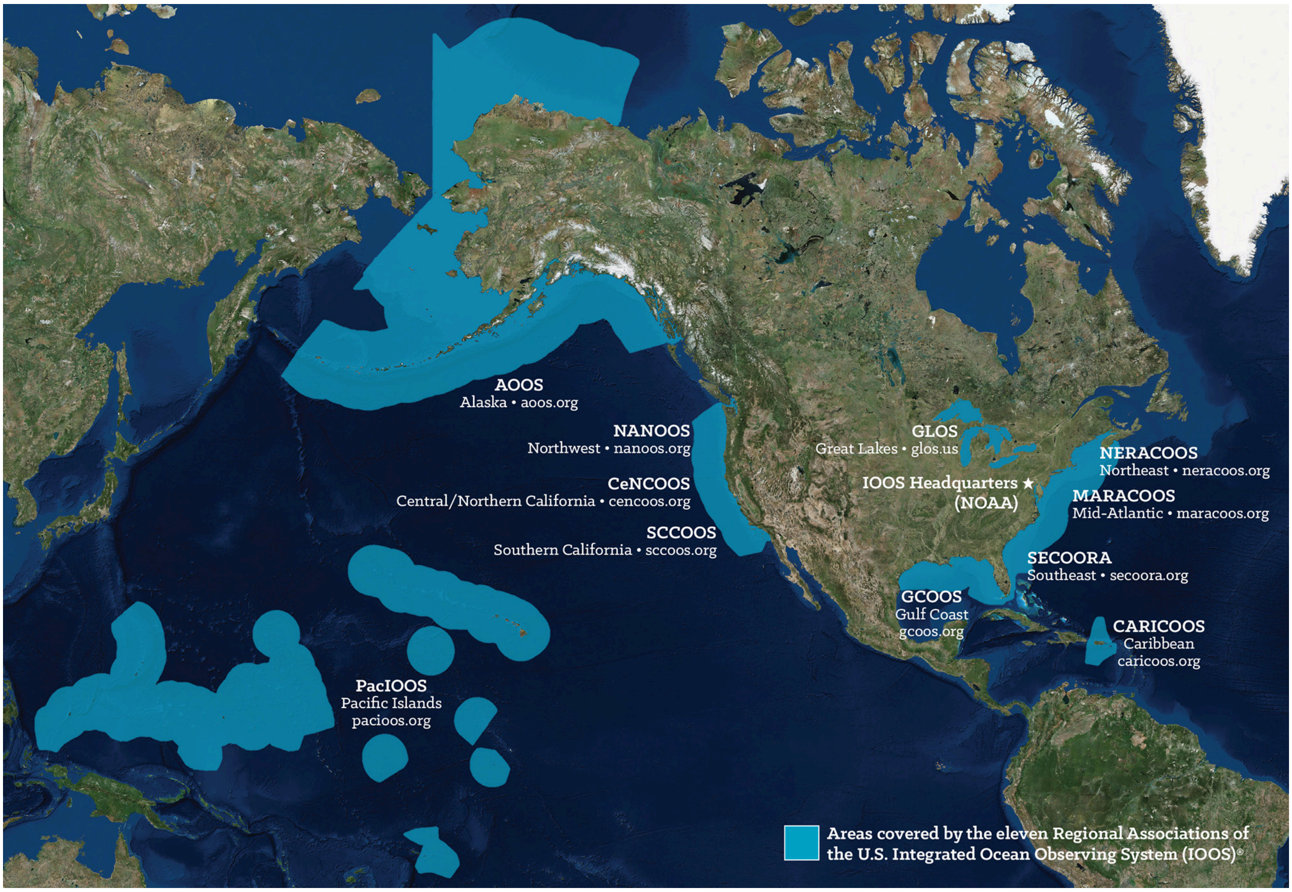

FIGURE 1 | Map of IOOS regional associations.

Managing potential conflict of interests is part of RA governance. As organizations that represent broad interests in a given region, RAs must function in a manner that is open and fair yet informed by leading experts in the field. Often those experts are the same people who receive funds to operate the system. Conflict of interest policies require these potential conflicts and others to be clearly stated and for affected individuals to recuse themselves from decisions from which they could benefit. Some RAs do not allow funded partners to serve on the board but have strategic planning committees that provide expert advice to the board.

Primary financial support for the operation, maintenance and expansion of the regional observing systems comes from a dedicated budget line in NOAA, the lead federal agency, through cooperative agreements that are completed every 5 years. These funds support the RA administrative offices that provide overall vision and direction for the organization, coordination, administration, and stakeholder engagement. The majority of the funds are awarded to partner institutions for observations, modeling, data management, and product development. About half of the RAs contract services from private IT companies while others have developed in-house capacity or work with research institutions.

U.S. IOOS and RA Funding Mechanisms

Awarding the 5-year cooperative agreements via a competitive process was initially designed to ensure that the RAs remain vital, up-to-date and responsive to regional needs. It has, however, proven to be a challenging method for funding a national network that strives to provide data and information to users in all 11 regions and to do so in a sustained and reliable manner. The fellowship of the RA directors, their commitment to the success of the entire network, and the support of the IOOS program has transformed the regional observing systems from a series of stand-alone efforts to a national network. The RAs work together to address their critical regional needs within this national network.

While funding from NOAA provides the base support for the program, it is not sufficient to address all existing needs. The coastal ocean and Great Lakes remain under-sampled. All regions seek additional funds to address the needs of the regions. RAs compete for grants, develop partnerships with federal agencies, non-profit organizations and industry to work on specific projects, and apply for support from philanthropic institutions. In one case, a RA received operational support for a mooring to monitor environmental conditions as a condition of the permit awarded for a natural gas terminal, and another RA

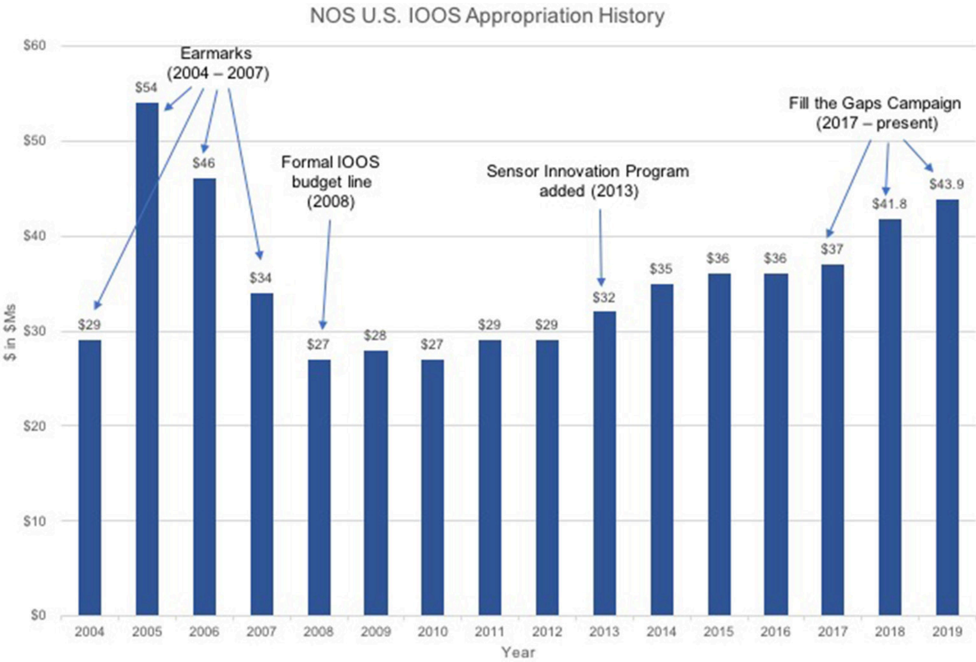

FIGURE 2 | IOOS Funding History.

received funds from a private foundation for a mooring. These funds are mostly for specific projects or for limited duration.

IOOS observations can be viewed on the IOOS environmental sensor map[5]. In 2018 the regional IOOS system partly or fully supported:

- 64 moored buoys,
- 21 wave buoys,
- 13 tide stations,
- 9 offshore towers with sensors for measuring water level, water temperature, salinity waves, meteorology, and dissolved oxygen,
- 130 fixed stations and sampling locations,
- 11 cruises during which samples were taken along a transect or off a research vessel, and
- 3 fixed satellite ground stations.

Despite the gains made, critical gaps remain. An Independent Cost Estimate conducted by NASA's Jet Propulsion Laboratory (JPL) in 2012 estimated that $542 billion was needed for a 15-year period to fulfill both the federal and non-federal needs for observing, the major portion of which includes the cost of satellite observations. JPL also estimated that $594 million per year was needed for the non-federal portion. As **Figure 2** shows, IOOS was initiated with funds in 2004 with Congressional-directed funding for a few regional systems. Four years later, IOOS became a formal part of the budget for the National Oceanographic and Atmospheric Administration, ensuring a long-term funding mechanism for the regional network and the national program.

[5]https://sensors.ioos.us/

Funds for a sensor innovation competitive grant program were added to the IOOS budget line in 2013 to foster technology innovation. The only increase in observing system support has been as result of a campaign to fill critical gaps in the High Frequency (HF) radar and profiling glider networks (see below). Still, the average annual costs for the regional component of IOOS for 2012 to 2017 were $25 million, far below the amount estimated by the JPL report. The RAs continue hearing from stakeholders about needs for better forecasts for weather, flooding, harmful algal blooms, ocean acidification, sea state conditions for maritime transportation, water quality and more.

In 2017, the RAs launched the "Filling the Gaps" campaign to address critical needs. The 5-year, scalable campaign initially focused on high-frequency radars, as IOOS operates the nation's system that provides surface current information in real time and for which there was a national plan. The U.S. Coast Guard uses the data for search and rescue and for spill response. At the direction of Congress, the campaign has expanded to also include profiling gliders. The campaign has brought in over $5 million to fill some of the critical gaps in high-frequency radar and glider operations.

Affiliated Programs to Support Technology Advancement

New and emerging technologies are key to the success and growth of IOOS. The RAs provide demonstration sites for new sensors, platforms and data management services and support technological transition to operations. IOOS RAs work with regional scientists, instrument manufacturers, and end-users to ensure responsiveness of emerging technologies to evolving scientific and stakeholder needs. Moreover, RAs communicate local and regional technological advancements to federal and global communities, thereby increasing exposure and application of new technologies. At the national level, IOOS works with partner agencies and NOAA programs to understand priority technology needs and advance the system through joint competitive programs and directed initiatives.

IOOS operates through existing federal partnerships and programs to support the development and operationalization of emerging technologies. For instance, the Alliance for Coastal Technologies (ACT), an IOOS partner, fosters the development and adoption of new technologies through performance evaluations and demonstrations. ACT identifies technology needs and supports the transition of emerging technologies to operational use. In recent years, ACT has advanced the operational use and application of nutrient sensors through the community-led competitive "Nutrient Sensor Challenge," a multi-agency [United States Environmental Protection Agency (EPA), the United States Geological Survey (USGS), the United States Department of Agriculture (USDA), the National Institute of Standards and Technology (NIST) and the National Oceanic and Atmospheric Administration (NOAA)-led U.S. Integrated Ocean Observing System (U.S. IOOS)] initiative to test and rank the performance and cost efficiency of *in situ* nutrient (i.e., nitrogen, phosphorus) sensors in the U.S. The winner was awarded a prize in 2017 and finalists are competing in a second phase, the Nutrient Sensor Action Challenge, aimed to test the application and usability of the sensors.

The IOOS Ocean Technology Transfer (OTT) and Coastal and Ocean Modeling Testbed (COMT) competitive programs provide funds for promising observing and computational technologies to be deployed in operational settings. The OTT program fosters technological advancement through an annual competitive award competition and has made significant contributions in the areas of ocean acidification (OA), harmful algal blooms (HAB), and nutrient monitoring, as well as regionally relevant technologies to track ice formation in the arctic and shark movement in the tropical Pacific. OTT support for Imaging Flow Cytobots (IFCBs), or *in situ* microscopes, has progressed the technology toward providing real-time plankton species classification and progress toward early warning systems of harmful species using environmental measurements. Similarly, COMT uses applied research and development to accelerate the transition of scientific and technical advances from the coastal ocean modeling research community to improved operational ocean products and services. Recent projects include biogeochemical modeling for hypoxia and other potentially hazardous events in the Gulf of Mexico and Mid-Atlantic regions and the comparison and integration of West Coast ocean forecast models.

EXAMINATION OF TWO REGIONAL ASSOCIATIONS

The following section provides examinations of two aspects of operating a Regional Association. The first focuses on the evolution of legacy observing systems that became the Southeast Coastal Ocean Observing Regional Association (SECOORA). The second explores how the Caribbean Coastal Ocean Observing System (CARICOOS) created a new system with available resources in response to the needs of local stakeholders.

Regional Ocean Governance Model for the Southeast Coastal Ocean Observing Regional Association (SECOORA)[6]

Unique Geography

The SECOORA region encompasses four states, forty-seven million people and spans the coastal ocean from North Carolina to the west coast of Florida. The region is vulnerable to hurricane hazards, potential impacts of oil drilling off Cuba and neighboring regions, harmful algal blooms and climate change. The region also includes many sensitive habitats including low-lying coastal land and corals that are already seeing significant ecological impacts from climate variability and other stressors.

The SECOORA geographic domain is linked through large-scale circulation patterns. The western boundary current (WBC) of the North Atlantic, comprised of the Loop Current/Florida Current/Gulf Stream system, interacts strongly with coastal waters, intimately coupling the SECOORA domain to the global circulation. Changes in shelf width across the region and changes in circulation with time modulate the degree to which the deep ocean interacts with the nearshore environment but throughout the region, shelf water properties reflect the WBC influence.

Numerous estuaries in the SECOORA footprint connect the watersheds of the southern Appalachian Mountains to the coastal waters. These varied estuarine systems, from broad lagoons to dendritic marsh systems with large tidal ranges, are also influenced by shelf processes and establish a strong connectivity between the land and the sea. The transition from the WBC in deep water to varied nearshore and estuarine environments can be complex and leads to a requirement that observations be collected from all these environments. The cross-shelf structure can be captured by measurements made within the WBC, on the outer, middle and inner continental shelf, and nearshore and within the estuaries.

A second aspect of this connectivity is in the atmosphere, where strong frontal passages impact ocean circulation in the Gulf and along the eastern seaboard. Strong surface winds such as those produced by tropical storms can induce upwelling/downwelling regimes in the SECOORA domain that affect the ecosystem in profound ways. Wintertime cyclogenesis also occurs over the Gulf Stream creating severe weather such as extratropical cyclones that impact both the Southeast and mid-Atlantic. Like tropical storms, these severe weather events (e.g., nor'easters), may result in loss of life and property in addition to significant economic consequences. Strong land/sea contrasts can produce localized weather patterns like the sea breeze/land breeze. Thus, implementing a strategy to acquire

[6]https://secoora.org/

marine atmosphere, estuarine and oceanographic observations in SECOORA that are linked to robust predictive models and decision making tools is essential to meeting user needs, including improving forecasting of severe weather events and marine conditions.

SECOORA Governance Structure

A defining characteristic of SECOORA is its status as an independent non-profit. SECOORA was incorporated, with South Carolina Sea Grant Consortium acting as the organization's fiscal agent, and transitioned to independent status in 2010. The founders of the organization prioritized the need to avoid bias, or the appearance of bias, in decision-making by transitioning the organization from its original fiscal home within a state institution to independent operation. This independent status means the staff of the Regional Association are employees of SECOORA, not one of the member institutions or stakeholder interests represented in SECOORA.

A 17-person Board of Directors elected by the members governs SECOORA. The Board appoints the Executive Director, who in turn, manages all SECOORA staff and contractors. The by-laws provide the overall organizational structure for SECOORA and outline member, board, and staff responsibilities. Members represent a cross-section of regional interests from private industry, academia, non-governmental organizations, and state and federal government.

SECOORA is a dues-paying membership organization, which may have impacted its membership. Some organizations that have interests in SECOORA activities like fishing clubs, river-keepers, small private companies and some state agencies, have indicated an inability or unwillingness to pay the $1,000 annual dues, even though they are very supportive of SECOORA and its activities. As one comparison, the neighboring Regional Association, Gulf of Mexico Coastal Ocean Observing System, which overlaps with SECOORA's West Florida Shelf area and does not require dues, has four times as many members. SECOORA is currently evaluating whether a change in dues requirements would impact membership. Of note, half of SECOORA's current members were founding members of the organization, indicating long-standing and active support of the organization and its mission.

The governing by-laws address balance on the Board of both sector and geographic representation. Equal numbers of Board seats are assigned to three sectors: (1) private industry, (2) academia, and (3) non-governmental organizations. The by-laws also assign one Board seat each for the states of North Carolina, South Carolina, and Georgia, and three seats for Florida, to address geographic representation. In practice, these rules have helped to meet the goals for balanced sector and geographic representation, however there is some bias. Originally, approximately half of SECOORA's members were from Florida and the state's population was approximately 45 % of the region's total population, factors which influenced granting Florida more seats. Today, 30% of SECOORA members are from Florida. Historically, the majority—currently 51%—of SECOORA's members are from the academic sector. However, because there are no sector limitations for the required geographic seats, academic members occupy the 83% of them, leading to an academic bias on the Board.

As a small independent organization, SECOORA has considerable flexibility in how it operates. Currently, the four full-time and one half-time staff work in three locations spread throughout the region, enabling SECOORA to maintain a physical presence in three of its four member states. The Executive Director, Financial Manager and part-time bookkeeper work from Charleston, South Carolina. The Regional Coastal Ocean Observing System Manager and the Communications Director work from Wilmington, North Carolina, and St. Petersburg, Florida, respectively. The distribution of staff throughout the regional domain helps ensure awareness of local and state-level priority issues, and interaction with key stakeholders unique to SECOORA's sub-regional states. Additionally, as the entire region is subject to impacts from tropical storms and hurricanes, the distribution of staff allows SECOORA to stay at least partially operational when major storms disrupt services in one of the staff work locations. This structure has also reduced overhead costs, enabling SECOORA to not only operate very efficiently but support a greater number of initiatives.

In summary, SECOORA's current governance structure is not perfect, but it works. The governing Board of Directors supports independent staff operations, resulting in a flexible low-overhead operation. The Board includes representatives of academic, private sector and other organizations including non-governmental and governmental institutions, although academic interests hold 53% of Board seats. SECOORA's dues requirement appears to have limited participation by some groups, which SECOORA is in the process of investigating, along with other possible changes to the by-laws that could impact future governance. Like most organizations, SECOORA is constantly evolving to stay current and meet the needs of its stakeholders and customers.

SECOORA is one example of how the IOOS RAs are organized. It shares similarities with the other RAs. About half of the RAs are incorporated as legal independent non-profit organization like SECOORA while the rest are organized through Memorandums of Agreement. Regardless of the legal structure, all RAs are governed by a set of by-laws and management boards that represent the range of stakeholder interests. SECOORA is one of the five RAs that collect membership dues.

Strengths and Challenges of SECOORA

Network

The most often cited benefit of membership in SECOORA, based on one-to-one interviews of current members, is the opportunity to network with (1) regional ocean and coastal experts, (2) various public, private and governmental representatives working in the southeast on ocean and coastal issues, and (3) everyday citizens and other users with needs for coastal and ocean data and information. The network has also spawned collaborations on grant proposals to various federal funding opportunities and more recently, to foundations. A public-private partnership between Surfline, Inc., SECOORA, and NOAA and other federal government representatives has resulted in an initiative utilizing expertise of the private sector to investigate the use of web cameras for various environmental monitoring applications. This initiative may result in a "new line of business" for the private sector partner as well as increase SECOORA's observing infrastructure to serve additional stakeholders, and support NOAA's weather forecasting mission.

SECOORA's regional network structure has also enabled SECOORA to support other regional networks that are in earlier/newer, or less stable stages of their development. Currently, SECOORA is the administrative home of the Southeast Ocean and Coastal Acidification network (SOCAN), the Southeast Disaster Recovery Partnership (SDRP), and the Florida Atlantic Coast Telemetry (FACT) Network. FACT originated as the Florida Atlantic Coast Telemetry Network but has since grown to include partners from the Bahamas to the Carolinas. Additionally, when the Governors' South Atlantic Alliance (GSAA) was operational, SECOORA was an active member and now serves as the data archive for the GSAA's work. The services and support SECOORA provides include administrative/fiscal, outreach, including internet and social media, logistic and data management.

The network of 11 RAs that comprise the IOOS Association is a significant strength of SECOORA and the other RAs. The national footprint of the IOOS Association enables broader support for challenges that maybe limited in scope. For example, Hurricanes Harvey, Irma and Maria in 2017 impacted the Gulf of Mexico, Southeast and Caribbean regions. The IOOS Association rallied in support of the impacted regions and a federal funding request to repair damaged observing infrastructure. Representatives in RAs not impacted by the 2017 hurricanes carried a message to Congressional members in their regions to bolster and broaden support for funding to repair critical observing infrastructure.

User connections in the southeastern united states

Like all IOOS Regional Associations, one of SECOORA's strengths is its regional scale, which enables close ties to users and other stakeholders. Members are engaged in their communities, regularly participate in local activities, and are aware of needs and challenges facing the region. However, because the region is large, and encompasses four states with wide-ranging habitats, coastal geomorphology and user populations, making decisions about where to invest limited resources is challenging. The need for objective, transparent user- and science-based mechanisms for determining priorities for the observing system was an initial challenge for the organization and remains one today.

Observing System Experiments (OSE), Observing System Simulation Experiments (OSSE), and/or system engineering could be utilized to determine what observing infrastructure should be prioritized (Halliwell et al., 2009, 2014). The designs of OSE and OSSE, however, are predicated on a specific question to be addressed (e.g., what is the impact of type of instrument used or the impact of frequency of deployments?) and may be biased by specific interests (Masutani, 2016). Because SECOORA—like the rest of the IOOS system—strives to address multiple societal needs, and hence address a variety of science questions at varying spatial and temporal scales, SECOORA would need to invest in numerous OSE and/or OSSE in order to effectively utilize them in decision-making. Given the immediate costs associated with OSSEs (Masutani, 2016), the need to do many of them focused on multiple questions, and SECOORA's present operational budget, it is cost-prohibitive for SECOORA to run a sufficient number of OSE and OSSE for them to be useful in SECOORA's decision-making and prioritization efforts. For SECOORA, it remains difficult to balance user needs, science-driven priorities, and sub-regional interests.

Sustained long-term observations

Sustained operation of ocean observations is a hallmark of SECOORA, which developed from several sub-regional predecessor observing programs including Southeastern Universities Research Association (SURA) Coastal Ocean Observing Program (SCOOP), Southeast Atlantic Coastal Ocean Observing System (SEACOOS) (Seim et al., 2009) and Coastal Ocean Research and Monitoring Program (CORMP). These legacy observing systems invested in four types of coastal observing infrastructure: ship-based measurements, moored buoys, coastal stations, and high-frequency radar (HFR). The routine ship-based measurements were discontinued in the early 2000s when funding declined for the sub-regional projects. To some extent, these areas are now covered by glider surveys. However, some of the stations established by these predecessor programs have now been sustained for 20 years, providing critical long-term coastal observing data records for the region. **Figure 3**, **Tables 2**, **3** provide details on the currently supported observing assets of SECOORA. In addition to moored, coastal and HFR stations, routine glider missions are supported. In 2018, SECOORA funded operations for 73 glider days, and provided data management support to transfer data to the IOOS Glider Data Assembly Center (DAC) for approximately 60 additional glider days funded by other sources. Gliders routinely measure temperature, salinity, dissolved oxygen, turbidity, colored dissolved organic matter, chlorophyll-a and also have Vemco mobile transceivers to listen for tagged marine life.

To improve SECOORA's delivery of real and near-real time data to stakeholders, SECOORA uses Google Analytics to track operational statistics, product usage, and outcome measures. These statistics are reviewed annually to assess end user needs, reevaluate priorities, and identify potential areas for growth. In 2016, SECOORA also implemented operational metrics for select sensors in the SECOORA network. Asset operators who receive funding from SECOORA are expected to meet or exceed the stated target metrics. To the extent possible, SECOORA metrics align with those recommended by IOOS. For HFR and moored buoys, SECOORA uses an operational uptime statistic of 85% or better where the definition of "uptime" varies according to infrastructure type. In the case of moorings, statistics are reported for each individual sensor and "uptime" is defined as the delivery of good or suspect data within 2 h of the targeted time. Bad data, as defined in the 13 available Quality Assurance of Real-time Oceanographic Data (QARTOD)[7] manuals are not counted. For HFR, "uptime" is measured by the return of data to the HFR

[7]https://ioos.noaa.gov/project/qartod/

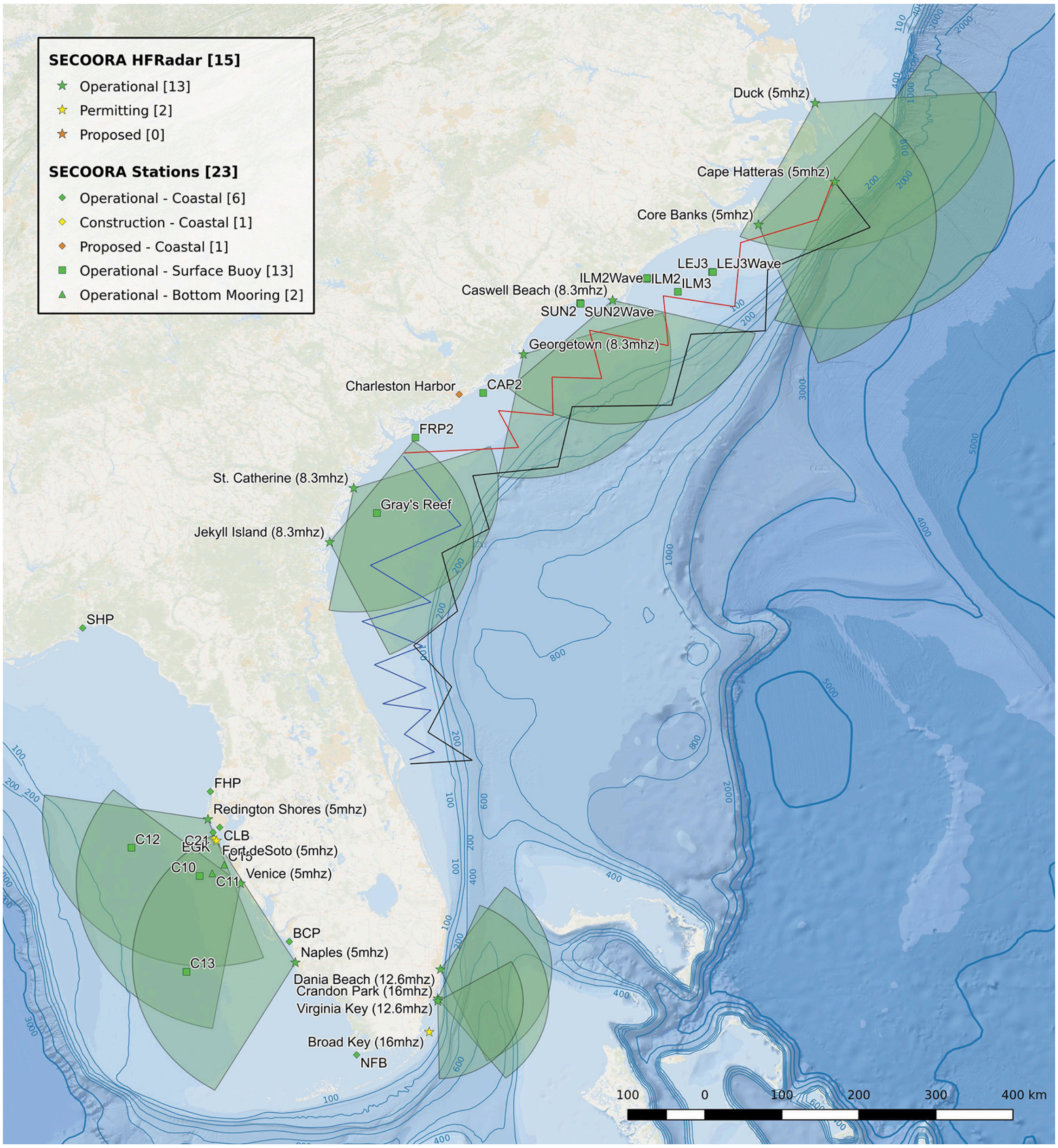

FIGURE 3 | The SECOORA geographic domain and observing infrastructure.

DAC. For gliders, SECOORA tracks operational days at sea and requires at least 75 days for the available funding. Data quality is not yet factored into the glider operational statistics as these metrics would need to be developed in coordination with the IOOS Glider DAC.

Challenges and leverage

The challenge of investing in sustained observations is considerable when annual budgets remain somewhat level. SECOORA has seen modest increases over the last decade averaging 3% annually, or \$100,000 dollars. Expanding the observing system to include stations in new locations has been practically impossible when the purchase price for a new station often exceeds \$100,000, and annual maintenance costs range in the tens-of-thousands of dollars. Even investing in new technologies and/or sensors has been cost prohibitive unless such purchases are leveraged from non-IOOS grants or programs.

One solution has been to leverage the observing assets of member institutions and federal agencies to operationalize underutilized equipment. This was the mechanism utilized to initiate SECOORA's glider observatory in 2016. Five member institutions with gliders acquired through other programs collaborated to propose regular missions in the Southeast. SECOORA has been able to provide operational funding to

TABLE 2 | SECOORA supported moored and coastal stations and measured parameters.

	Operator**	Wind speed, gust, direction	Air temp	Barometric pressure	Relative humidity	Short wave/long wave radiation	Water temp	Currents	Waves	Conductivity/ Salinity	Water level	Fish acoustic sensors
MOORED STATIONS												
LEJ3—Outer Onslow Bay, NC	UNCW	X	X	X	X		X			X		X
LEJ3Wave—Outer Onslow Bay, NC	UNCW						X		X			
ILM3—Outer Onslow Bay, NC	UNCW	X	X	X	X		X			X		X
ILM2—Inshore Onslow Bay, NC	UNCW	X	X	X	X		X			X		X
ILM2Wave—Inshore Onslow Bay, NC	UNCW						X		X			
SUN2—Northern Long Bay, SC	UNCW	X	X	X	X		X			X		X
SUN2Wave—Northern Long Bay, SC	UNCW						X	X	X			
CAP2—Inshore Capers Island, SC	UNCW	X	X	X	X		X			X		
FRP2—Inshore Fripp Island, SC	UNCW	X	X	X	X		X			X		
OB27—Onslow Bay, NC*	UNCW						X	X	X	X		X
C10—WFS Central nearshore, FL	USF	X	X	X		X	X					
C12—WFS Central offshore, FL	USF	X	X	X		X	X					
C13—WFS South, FL	USF	X	X	X		X	X					
C11—WFS Subsurface, FL*	USF						X	X	X			
C15—WFS Subsurface, FL*	USF						X	X	X			
C21—Tower, FL*	USF	X	X	X	X		X	X	X			
COASTAL STATIONS												
SHP—Shell Point, FL	USF	X	X	X							X	
EGK—Egmont Key, FL	USF	X	X	X							X	
FHP—Fred Howard State Park, FL	USF	X	X	X							X	
CLB—Clam Bayou, FL	USF	X	X	X			X			X	X	
BCP—Big Carlos Pass, FL	USF	X	X	X							X	X

**Non real-time station.*
*** UNCW-University of North Carolina Wilmington; USF-University of South Florida.*

TABLE 3 | SECOORA supported high frequency radar stations.

HFR name	Operating institution	Location (lat/long)	Location (city/state)	Transmit frequency
DUCK	UNC-Chapel Hill	36.18/−75.75	Duck, NC	4.537
HATY	UNC–Chapel Hill	35.26/−75.52	Cape Hatteras, NC	4.575
CORE	UNC-Chapel Hill	34.76/−76.41	Core Banks, NC	4.537
CSW	University of South Carolina	33.88/−78.02	Caswell Beach, NC	8.225
GTN	University of South Carolina	33.25/−79.15	Georgetown, SC	8.333
CAT	University of Georgia Skidaway Institute of Oceanography	31.69/−81.13	St. Catherine, GA	8.452
JEK	University of Georgia Skidaway Institute of Oceanography	31.09/−81.41	Jekyll Island, GA	8.395
STF	University of Miami	26.08/−80.12	Dania Beach, FL	12.7
VIR	University of Miami	25.74/−80.15	Virginia Key, FL	12.7
CDN	University of Miami	25.71/−80.15	Crandon Park, FL	16
NKL*	University of Miami	25.19/−80.35	North Key Largo, FL	12.7
RDSR	University of South Florida	27.83/−82.83	Reddington Shores, FL	4.9
VENI	University of South Florida	27.08/−82.45	Venice, FL	4.9
NAPL	University of South Florida	26.16/−81.81	Naples, FL	4.9

Permit pending to install.

support three missions annually in the very under-observed South Atlantic Bight.

Opportunities for the future

Effective planning will help ensure new opportunities can be effectively realized. SECOORA is in the process of updating its Regional Coastal Ocean Observing Plan. Scheduled for completion in 2019, this plan will present the options for both sustaining existing and expanding coastal and ocean observing operations in the Southeast. Users are being engaged to identify priority needs for data and information. SECOORA anticipates waves, acoustics and ocean sound, harmful algal bloom (HAB) monitoring, water level measurements, ocean and coastal acidification, and modeling to improve weather, water level and human health forecasts to all be key components of the plan. The challenge, as always, will be prioritizing needs. User-driven and science-based remain the guiding principles for making investment decisions.

Ensuring that SECOORA's governance processes effectively engage users, members and new stakeholders will create additional opportunities. A transition from an academic sector majority on the Board to more balanced representation from private, government and non-profit sectors could potentially broaden both the impact of and opportunities for SECOORA. A challenge in the past has been maintaining long-term engagement since interests are often narrow within stakeholder groups, but SECOORA's mission is broad. Similarly, if available funding and capacity remain relatively level, recruiting new members and additional users not served by the existing system can create false expectations for growth. Transparent and inclusive processes for governance and prioritization have helped to address these challenges.

As discussed in other sections of this paper, SECOORA expects that new and cheaper technologies will enable more observing of the physical coastal, oceanic and atmospheric parameters currently being collected as well as increased observations of biological, water chemistry, water quality, and human use parameters. Building on existing core infrastructure—both physical as well as people—to add sensors and other new observing technologies will leverage the historic investments in the region to meet additional needs.

Balancing Diverse Stakeholder Needs in the Caribbean Coastal Ocean Observing System (CARICOOS)[8]

The Caribbean Coastal Ocean Observing System (CARICOOS) region encompasses the U.S. Caribbean Archipelago hosting two territories, Puerto Rico and the U.S. Virgin Islands, with a combined population of approximately 3.8 million citizens. As insular communities, dependence on coastal resources is well-ingrained in its cultural richness and economy. Coastal waters provide for transportation and host neotropical ecosystems which offer essential ecosystem services including aesthetic appeal that fuels recreational activities/industries, fisheries and coastal protection among others.

Governance Structure Implications

Initial funding by Ocean.US required the identification and prioritization of stakeholder needs in the region, the development of a plan toward meeting these and formalization of a governance structure. The latter, initially known as the Caribbean Regional Association (CaRA), was responsible for overseeing the early implementation of the Caribbean Coastal Ocean Observing System. For further details on the system's early organization and development see Watlington et al. (2008) and Morell et al. (2015). At present CARICOOS continues being an open association of all interested stakeholders while its governance has evolved into a fully vested 501(c)(3) tax-exempt organization led by a 15 member board of directors elected by association members and which represent its diverse stakeholder sectors. The intrinsic

[8]https://www.caricoos.org/?locale=en

capability for direct contact with stakeholders and detailed knowledge of existing resources within the region buttressed the overarching mission: identify high priority coastal information needs and provide cost efficient solutions for meeting these.

Improving the safety of coastal communities and marine operations, enhancing the economy through increased efficiency of the latter and protecting the environment were identified as the overarching goals of the regional observing system. Major achievements toward these goals include the deployment of data buoys and meteorological stations at representative areas and the operational implementation of high-resolution wave and weather models capable of filling observational gaps and providing accurate wind and wave and nearshore breaker height forecasts. A storm surge atlas is now in use by state and federal agencies. Also, CARICOOS became a partner in NOAA's Ocean Acidification Program.

Unique Stakeholders and Geography

CARICOOS geographical setting, embedded in the hurricane alley and located at the boundary between the Caribbean Sea and the Western Tropical Atlantic, results in dynamic and often extreme coastal ocean and weather conditions. As an insular region, the U.S. Caribbean Archipelago lagged behind continental areas in having access to real-time and accurately forecasted information in support of decision-making and minimizing threats to coastal communities, while also optimizing the use of local resources. The advent of the U.S. Integrated Ocean Observing System provided a unique opportunity for addressing the absence of coastal ocean observing assets to meet high priority needs in Puerto Rico and the U.S. Virgin Islands. Since early on, data products from CARICOOS buoys and coastal meteo-stations were readily incorporated as essential tools by diverse sectors including the U.S. Coast Guard, the National Weather Service San Juan Weather Forecast Office, Harbor pilots, state agencies, and recreational operators as well as individuals. Likewise, coastal wave and weather forecasts at spatial resolutions appropriate for coastal and nearshore operations were readily recognized as useful planning support. Particular attention has been given to the incorporation of said data streams, along with those from more recently deployed assets (see **Figures 4**, **5**), federal platforms and data provided by partners into readily accessible products aboard a user-focused webpage (http://caricoos.org) and apps. **Figures 4**, **5** depict the location of existing observational assets in the region and system progression metrics including IOOS support, number of observational platforms and pageviews for CARICOOS.org and National Data Buoy Center webpages for CARICOOS assets. Observational assets include meteo-stations, data buoys, HFRs and AUVs, some of which are supported by but were not acquired with IOOS funds. **Table 4** (CARICOOS Measured Parameters) includes a list of observing platforms and parameters reported by these.

Strengths and Solutions

In its second developmental phase, CARICOOS' initiatives responded to critical data needs from its largest stakeholder sectors; those living, working and/or enjoying the region's wealth of coastal areas including beaches, ports, and harbors. Specific stakeholder data and information needs addressed include,

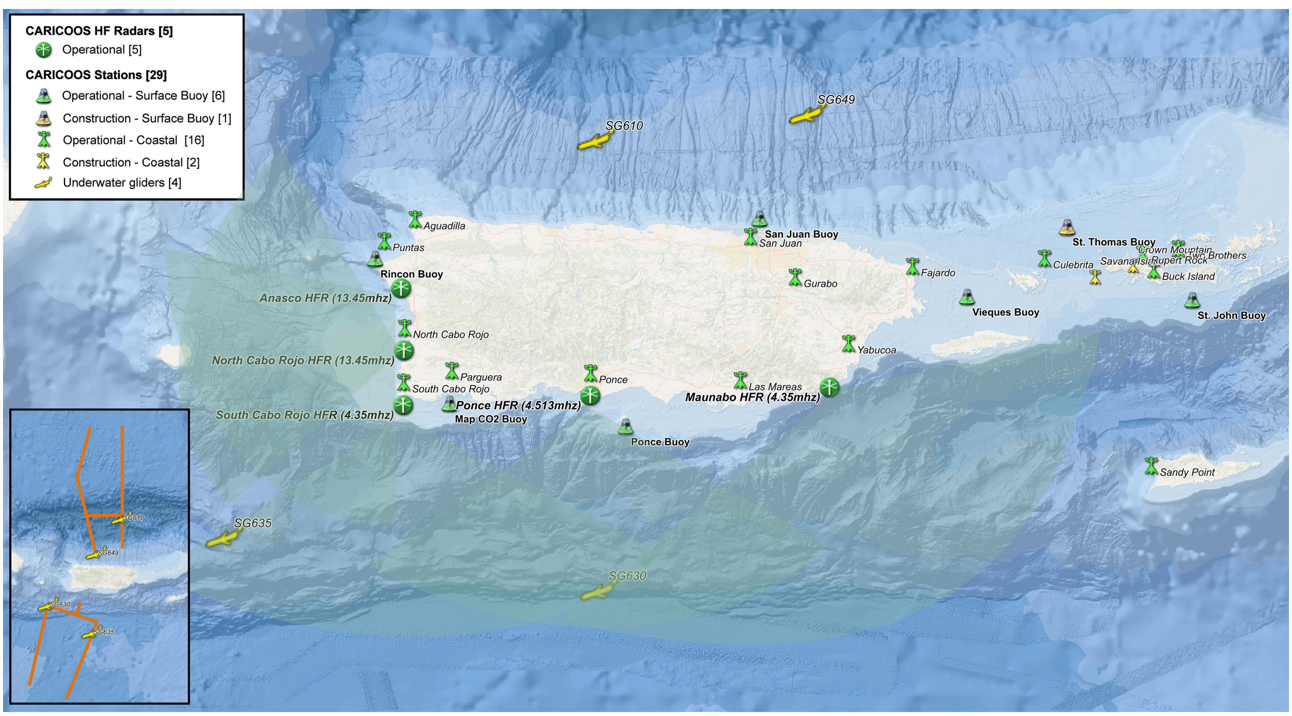

FIGURE 4 | The (CARICOOS) geographic domain and observing infrastructure.

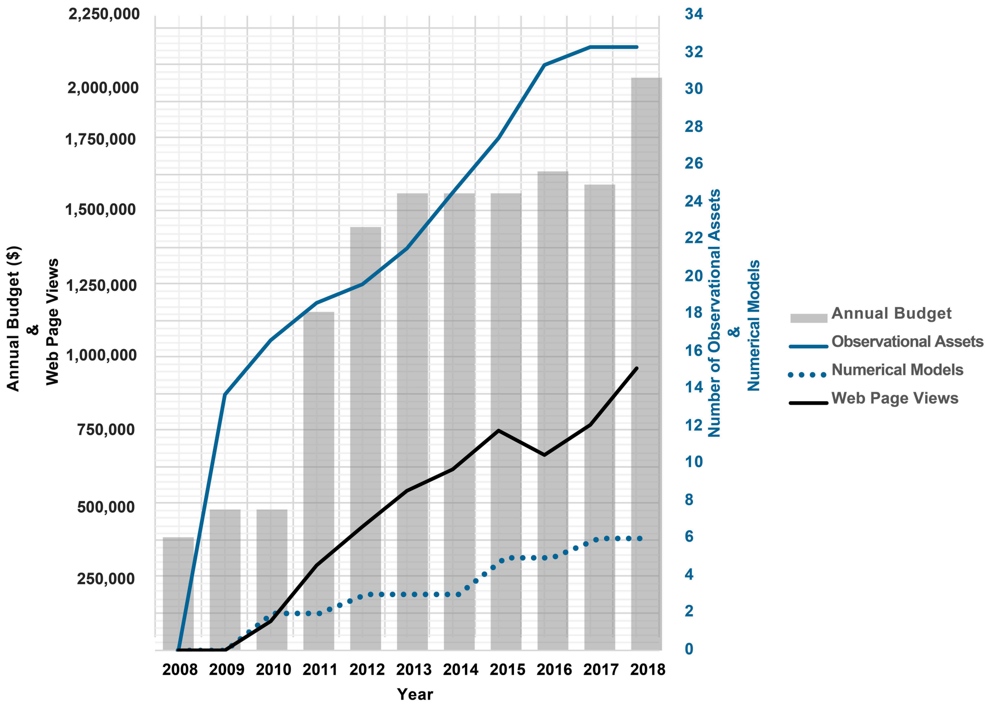

FIGURE 5 | CARICOOS website use compared to annual budget.

among others, an elevated per capita drowning incidence, coastal erosion for the west and north shores, challenging conditions while navigating channels and harbor approaches, decisional support for scheduling recreational operations and storm surge maps for planning emergency management response.

Technical developments included enhancing CARICOOS Nearshore Wave and Weather Research and Forecasting (WRF) weather models to yield very high-resolution, 60 to 120 m and 1 km, respectively, forecasts. Moreover, with matching support from the University of Puerto Rico Sea Grant Program, CARICOOS developed a nearshore breaker forecasting system warning swimmers of potential hazardous nearshore currents. Also, the storm surge modeling program revised the computational grids and issued maps for all the coasts for Categories 1 to 5 hurricanes.

Observational capabilities installed during this phase include three long range CODAR HF radars off the south coast of Puerto Rico. These report surface current measurements up to 250 km from the coast. Another addition, with co-funding by the U.S. National Science Foundation, included the development of high-resolution jet ski-based bathymetric surveying and sonar mapping system for monitoring coastal erosion and the potential need for rapid port restoration. The recent implementation, in collaboration with NOAA Atlantic Oceanographic and Meteorological Laboratory, of an ocean glider program for observing the open ocean water column properties for the improvement of hurricane intensity forecasts also provides for monitoring ocean warming and improved understanding of mesoscale processes driving near-coastal hydrodynamics. Subsurface temperature observations augment operational NOAA's coral reef watch efforts reporting sea surface temperature anomalies and issuing bleaching alerts and warnings.

Challenges and Limitations

After major advances in addressing essential immediate stakeholder needs, several issues remain. These include current and foreseeable water quality issues potentially threatening ecosystem and human health. Of particular concern are sediment loading and coliform contamination, thermal stress, and hypoxia and ocean acidification. Observing these may require the identification of readily monitored optical and other parameters or proxies that when coupled to hydrodynamic modeling may provide for understanding connectivity between inshore waters, often more severely impacted by anthropogenic activities, and nearby beaches, sensitive coral reefs and seagrass ecosystems. Very high resolution numerical modeling is strongly supported as a mechanism to address these issues. Short-term deployments of observing assets, including coastal drifters, acoustic Doppler current profilers, and pressure sensors can provide validation essential for accurate nowcasting and ecosystem forecasting.

The Caribbean Islands are surrounded by a complex non-linear hydrodynamic matrix arising from the interaction of the North Equatorial Current with the northeastern coast of South America and later on with a dense arc of islands with steep bathymetric profiles, the Eastern Caribbean Leeward Islands. In addition, the region experiences seasonal arrival of major river plumes originating in the Amazon and Orinoco rivers. These

TABLE 4 | CARICOOS measured parameters.

	Wind speed, gust, direction	Air temp	Barometric pressure	Relative humidity	Short wave/ long wave radiation	Water temp	Currents	Waves	Conductivity/ Salinity	Water level	Fish acoustic sensors
PUERTO RICO											
PR1—Ponce, PR	X	X	X			X	X	X	X		
PR2—San Juan, PR	X	X	X			X	X	X	X		
PR3—Vieques, PR	X	X	X			X	X	X	X		
181P1—Rincón, PR								X			
XAGU—Aguadilla Jetty, Aguadilla, PR	X	X	X	X							
XYAB—Port of Yabucoa, Yabucoa, PR	X	X	X	X							
XREY—Marina Puerto del Rey, Fajardo, PR	X	X	X	X							
XMRS—Las Mareas, Guayama, PR	X	X	X	X							
XJUA—San Juan NavAid, San Juan, PR	X	X	X	X							
XGUR—Gurabo, PR	X	X	X	X							
XCUL—Culebrita Island, PR	X	X	X	X							
XCDP—Club Deportivo del Oeste, Cabo Rojo, PR	X	X	X	X							
PUNTAS—Rincón, PR	X	X	X	X							
MAGUEYES—Magueyes Island, Lajas, PR	X	X	X	X							
E7866—Cabo Rojo Lighthouse, Cabo Rojo	X	X	X	X							
E9889—Tres Palmas Reserve, Rincón	X	X	X	X							
E7791—Ponce Yacht Club, Ponce	X	X	X	X							
FURA—Añasco							X				
CDDO—Club Deportivo del Oeste, Cabo Rojo							X				
FARO—Los Morrillos Lighthouse, Cabo Rojo							X				
PYFC—Ponce Yacht Club, Ponce							X				
MABO—Punta Tuna Lighthouse, Maunabo							X				
SG635—Underwater glider						X			X		
SG630—Underwater glider						X			X		
SG 610—Underwater glider						X			X		
SG649—Underwater glider						X			X		

(Continued)

TABLE 4 | Continued

	Wind speed, gust, direction	Air temp	Barometric pressure	Relative humidity	Short wave/ long wave radiation	Water temp	Currents	Waves	Conductivity/ Salinity	Water level	Fish acoustic sensors
U.S. VIRGIN ISLANDS											
VI1—St. John	×	×	×			×	×	×	×		
XWGO—Crown Mountain, St. Thomas	×	×	×	×							
XSAV—Savana Island, St. Thomas	×	×	×	×							
XRUP—Ruperts Rock, St. Thomas	×	×	×	×							
XCRX—Sandy Point NWR, St. Croix	×	×	×	×							
XBUK—Buck Island, St. Croix	×	×	×	×							
XBRO—Two Brothers, St. Croix	×	×	×	×							

interactions generate a phenomenal diversity of vortices, jets, and internal waves which coupled to massive continental riverine input poses a formidable challenge to its proper understanding; a requisite for forecasting shelf and inner water processes including hydrodynamics, extreme temperature events and biogeochemical processes among others.

An additional challenge is communicating with data users with limited technical knowledge or scope of interest. While the CARICOOS website presents data and forecasts at their full temporal and spatial resolution, which is widely recognized and used, many stakeholders have indicated that the complexity of the web page and products presented represents a barrier to its use. In response to the above issue, CARICOOS plans to develop apps for the currently most popular platforms, tablets and smartphones. A beach app "Pa' la Playa" has been recently released and widely accepted. A boaters/fishers app is currently in development.

Opportunities for Future Improvements

While designing its next implementation phase, CARICOOS recognizes the need for assessing forcing by the above processes but also budgetary constraints which preclude "*in situ*" high frequency observing by deep water buoys or shipboard measurements. These observations can be provided, in a cost effective manner, by remotely operated observing assets such as radars capable of reporting conditions at a high spatial and temporal resolution. New technologies are being explored which can provide the answer when coupled with required validation and ancillary shipboard and remotely sensed data: long range high frequency radars and Autonomous Underwater Vehicles (AUVs). These can yield real-time data of immense value but also provide for the improvement, via assimilation, of much needed operationally accurate hydrodynamical modeling. Other expected observational and forecast outcomes include the quantitative shelf-ocean exchange of salt, heat and organic constituents.

After an initial phase where AUV subsurface ocean structure information has proven to significantly improve hurricane intensity forecasts, the operational assimilation of glider data is foreseen to require an expansion of glider observations, particularly in the most "hurricane upstream" U.S. Exclusive Economic Zone. This opportunity will require growth in both expertise and operational resources for glider deployments, refurbishments and related activities.

An emergent issue with deep economic impact, the arrival of massive floating mats of the algae *Sargassum spp.* into the region, has become a recurrent problem for the beach-oriented tourism industry. Other less well-known outcomes include hypoxia and increased acidification resulting from the increased organic carbon loading in reefs, seagrasses and mangroves. CARICOOS is being challenged with providing forecasts for municipalities and hotels to deploy beach cleaning operations but also for nascent efforts for extracting products and/or energy from said algae. A pilot project to track floating algae identified with remotely sensed imagery and HFR derived surface currents has recently commenced. The use of aerial drones for algal mat location has also been proposed.

LOOKING TO THE FUTURE OF IOOS

Climate change means that the coasts, oceans, and Great Lakes of the future will not be the coasts, oceans, and Great Lakes of the past or present. Adapting to these changing environments and their changing uses is a key challenge for IOOS to ensure production, integration, and communication of information that is fit for purpose. Increasing sensing capabilities, autonomous operations, and artificial intelligence have the potential to transform observing systems over the next 20 years.

The U.S. National Climate Assessment of 2014 (Melillo et al., 2014) (the 2018 Assessment was not publicly available at the time of writing) outlined many of the threats and challenges that will continue into the future. They included;

1. Rising ocean temperatures—with the increase in ocean temperatures over the last century continuing impacting climate, ocean circulation, chemistry, and ecosystems.
2. Ocean and coastal acidification—altering marine ecosystems in significant but uncertain ways.
3. Habitat change and loss—leading to alterations in distribution, abundance, and productivity of many marine species.
4. Increased risk of diseases—for humans and marine life linked to increases in sea surface temperature.
5. Economic impacts—due to different conditions increasing costs to industry and disrupting public access, and enjoyment.
6. Rising sea levels—threatening and disrupting coastal infrastructure, vulnerable habitats, and ecosystems, as well as coastal economies that humans depend on.
7. Increased human pressure on the coastal zone—with more than 1.2 million people moving to the coasts each year and the additional 180 million people taking vacations in coastal areas.

Timely detection of change is essential for optimal management. However, current observing systems often lack the ability to rapidly distinguish alterations due to lack of temporal or spatial resolution. This is especially the case with biological observations. While many regional observing systems are capable of resolving rapid changes in hydrodynamics and water masses, detection of ensuing ecosystem shifts rely on infrequent ship based surveys unable to resolve variability at an appropriate temporal frequency. Ultimately, with our current capacities, changes in our coastal ocean and Great Lakes ecosystems will be statistically elucidated well after the fact, hampering appropriate and timely management actions.

The IOOS enterprise provides a nimble framework to enable evolution of observing systems to meet changing needs. The current foundation with all 11 regions certified, established engagement with stakeholders, the ability to innovate with new observing technologies and novel ways to communicate outcomes, all support the blue economy and are primed to adapt to future challenges. As the system further develops, many opportunities will arise to improve on current capabilities. Greater coordination between observing system components, including between regions and with global observing systems elements, will increase efficiencies and the delivery of information to users. Working toward a common framework for the management of data will be key, allowing technologies and products prototyped in one region to be rapidly deployed across the enterprise.

At the outset of IOOS approximately two decades ago it would have been hard to envisage the system of systems that exist today. Similarly, in the next 10 to 20 years, as sensors and platforms get smaller, more affordable, reliable and autonomous, an even more integrated ocean observing system will emerge. One can imagine a geostationary satellite continuously monitoring coastal waters at higher temporal, spatial, and spectral resolution than we have today. Analysis by an automated intelligent system detects the signature of a potential harmful algal bloom in offshore waters, triggering responses by other autonomous system assets. Unmanned aircraft systems, commonly called drones, are dispatched from autonomous maintenance hangers located along the coast targeted with rapidly mapping the spatial extent of the bloom at greater resolution and under clouds where the satellites cannot see. Other autonomous vehicles both on and below the surface are simultaneously retasked from their routine monitoring lines with observing the bloom. The surface vehicles with a greater payload measure a broader suite of parameters than the subsurface ones. Forecasts from regional models that assimilate observations including those from long time-series ecosystem monitoring moorings and offshore developments such as wind farms and aquaculture sites, provide key inputs for the tasking of the autonomous platforms. Visual and molecular techniques including eDNA confirm the presence of a Harmful Algal Bloom (HAB). A drone capable of operating in the air and subsurface is sent out to collect a series of water samples from hotspots to be returned to shore for analysis and archiving. HAB observations are assimilated into nowcast and forecast systems and likely scenarios produced.

Appropriate management and industry responses are developed and assets staged ready to respond. All of this is achieved without input from human operators. Alerts are subsequently sent to the system's operations staff, shellfish and fisheries managers, as well as the systems and staff at aquaculture sites (both nearshore and offshore) and the local tourism industry. As a result, millions of dollars are saved removing aquaculture stock before the bloom hits and redirecting tourists to areas unaffected by the bloom. This is just one potential application of a multi-use integrated ocean observing system of the future. Similar workflows can be envisaged to bring ships safely and efficiently into harbor, rescue those lost at sea, prepare local Weather Forecast Offices and emergency managers for storms and coastal flooding, and implement ecosystem based management to empower the blue economy and sustainable use of the coastal ocean and Great Lakes.

REFLECTIONS AND COMMENTS

Examining the past two decades of IOOS development, several observations can be made.

'One size' does not fit all. Coastal and ocean ecosystems, infrastructure, cultures and demographics vary widely across the US. The IOOS framework ensures consistent national goals and objectives while allowing for regional prioritization and implementation. The regional certification process assures the consistency necessary to enable RAs to effectively engage federal programs but does not dictate how and what the RAs must prioritize while addressing key issues identified by stakeholders.

The need for coastal observing is increasing, along with the global population and need for access to information. Timely and reliable information is needed to address the growing number of people under threat from coastal floods and extreme storms, assess changing fisheries and their ecosystems, detect and respond to harmful algal blooms and to support safe maritime operations. Investment in the IOOS enterprise over the last 20 years has established a strong foundation but gaps remain in many geographic areas as well as in the types of parameters routinely measured. The "Filling the Gaps" campaign is helping to address some of these needs by increasing funding for new regional observing infrastructure and its maintenance. However, the campaign is focused on surface current mapping and glider transects and does not address the need for other observing infrastructure, including the federal portion of the system. Repairs and upgrades to the existing and aging infrastructure that comprises the regional component of IOOS, and improved data integration and product delivery are also needed.

Determining the value of ocean and coastal observations is challenging. IOOS is a single system that supports the missions of many federal, tribal, state, non-profit and for-profit entities. IOOS observations support weather forecasting, maritime operations, search and rescue, detection of harmful algal blooms and more. Valuation of one observation to the nation or to a private company cannot be easily calculated since an integrated forecast or product is generally what is valued or sold. IOOS is not the agency issuing or selling the forecast or product, so its contribution can be invisible to those assessing profit and loss, cost and benefit. Establishing meaningful and measurable metrics at the beginning of the program would have provided a baseline for tracking the impact and value of the system. **The unique design of the IOOS enterprise is working well** as demonstrated by the longevity of the program, increasing data resources provided by the RAs, and increasing federal funding for the program. By linking the resources and expertise of 17 federal agencies with a national network of 11 regions, IOOS enables results that would not otherwise exist. National data assembly centers exist for gliders, high frequency radar and other environmental sensors and data sets[9]. The structure allows for both bottom-up and top-down approaches that promote efficiency by leveraging investments at the Federal, regional and local levels, and allow for tailored responses to the diverse needs of users around the country. Decisions about how to design and operate an integrated system are driven by the requirements of stakeholders. For national missions and goals, federal funding agencies establish requirements. To fill gaps in national programs and to generate data to meet local needs, decisions are best made at the regional scale where RAs can work with partners to determine priorities, integrate new technologies into existing systems and leverage existing resources. The evolution of, challenges, and successes of IOOS offer useful insights for other new and growing systems.

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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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[9]https://ioos.us/

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REVIEW
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Global Observations of Fine-Scale Ocean Surface Topography With the Surface Water and Ocean Topography (SWOT) Mission

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The future international Surface Water and Ocean Topography (SWOT) Mission, planned for launch in 2021, will make high-resolution 2D observations of sea-surface height using SAR radar interferometric techniques. SWOT will map the global and coastal oceans up to 77.6° latitude every 21 days over a swath of 120 km (20 km nadir gap). Today's 2D mapped altimeter data can resolve ocean scales of 150 km wavelength whereas the SWOT measurement will extend our 2D observations down to 15–30 km, depending on sea state. SWOT will offer new opportunities to observe the oceanic dynamic processes at scales that are important in the generation and dissipation of kinetic energy in the ocean, and that facilitate the exchange of energy between the ocean interior and the upper layer. The active vertical exchanges linked to these scales have impacts on the local and global budgets of heat and carbon, and on nutrients for biogeochemical cycles. This review paper highlights the issues being addressed by the SWOT science community to understand SWOT's very precise sea surface height (SSH)/surface pressure observations, and it explores how SWOT data will be combined with other satellite and *in situ* data and models to better understand the upper ocean 4D circulation (x, y, z, t) over the next decade. SWOT will provide unprecedented 2D ocean SSH observations down to 15–30 km in wavelength, which encompasses the scales of "balanced" geostrophic eddy motions, high-frequency internal tides and internal waves.

This presents both a challenge in reconstructing the 4D upper ocean circulation, or in the assimilation of SSH in models, but also an opportunity to have global observations of the 2D structure of these phenomena, and to learn more about their interactions. At these small scales, ocean dynamics evolve rapidly, and combining SWOT 2D SSH data with other satellite or *in situ* data with different space-time coverage is also a challenge. SWOT's new technology will be a forerunner for the future altimetric observing system, and so advancing on these issues today will pave the way for our future.

Keywords: ocean mesoscale circulation, satellite altimetry, SAR-interferometry, tides and internal tides, calibration-validation

INTRODUCTION

Over the last 25 years, satellite altimetric sea surface height (SSH) observations have greatly advanced our understanding of the large-scale ocean circulation and its interaction with the larger mesoscale dynamics (Fu and Cazenave, 2001; Morrow et al., 2018b). These SSH observations reflect the ocean surface pressure field and give us the ability to monitor depth-integrated ocean dynamics. Indeed altimetric SSH is the only satellite observation that so clearly responds to both surface and deeper ocean changes. Today, the noise of the classical along-track altimetric observations as well as the distance between groundtracks limits our observation of the 2D SSH field to scales greater than 150–200 km at mid-latitudes (Chelton et al., 2011). In parallel, ocean models are evolving, and global high-resolution, high-frequency models, with and without tides, are now available (e.g., HYCOM at 1/25° – Chassignet and Xu, 2017; Arbic et al., 2018; 1/48° MITgcm; 1/12° NEMO – Mercator Ocean). Yet the dynamics of these evolving high-resolution models cannot be validated today, due to the lack of global observations at these finer scales.

The future SWOT SAR-interferometry wide-swath altimeter mission is designed to provide global 2D SSH data, resolving spatial scales down to 15–30 km depending on the local SSH signal levels and measurement noise, which is a function of sea state; (Fu et al., 2012; Fu and Ubelmann, 2014, see section "Measurement Errors, SWOT Simulator, and Effective Spatial Resolution" for more details). SWOT observations will fill the gap in our knowledge of the 15–150 km 2D SSH dynamics, which are important for setting the anisotropic structure of the ocean horizontal circulation and for understanding the ocean's kinetic energy budget. Smaller-scale horizontal gradients can also be linked to energetic vertical velocities and tracer transports (Lévy et al., 2012a), and understanding the ocean stirring and convergence at these finer scales is important for global tracer budgets, biogeochemical applications, and climate.

As the name suggests, the Surface Water and Ocean Topography (SWOT) mission will bring together two scientific communities – oceanographers and hydrologists. For the hydrology community, SWOT SAR interferometric data will enable the observation of the surface elevation of lakes, rivers, and floodplains, and will provide a global estimate of discharge for rivers >100 m wide, and water storage for lakes >250 m^2. SWOT will also provide unprecedented observations in coastal and estuarine regions, of interest to both communities. The 3-years of repeat data will allow a better estimate of the mean sea surface and marine geoid; the high latitude coverage should allow a better assessment of the ice caps up to 78°N and S, and may even be used for estimating sea-ice freeboard and other parameters. The science objectives covering all disciplines are outlined in the SWOT Mission Science Document (Fu et al., 2012) and in Morrow et al. (2018a).

The SWOT Science Team has been preparing for this mission and its technical and scientific challenges since 2008, and the mission was introduced in the OceanObs09 whitepaper (Fu et al., 2009). In the first part of this 2019 white paper, we will give a brief introduction to the SWOT science objectives and its observing system and errors. We will highlight how SWOT observations may be used in conjunction with other observations to improve our understanding of the ocean energy cascade, internal gravity waves, and ocean fronts, and then consider the challenges in reconstructing the fine-scale upper ocean circulation with SWOT and models. This review paper will also address how SWOT and the *in situ* observing system may be used to better understand the vertical structure associated with the fine-scale SWOT SSH. In particular, the first 90 days of the mission will have a 1-day repeat phase, when the rapid evolution of these fine-scale dynamics can be observed. The calibration and validation (CalVal) of SWOT will be discussed, as well as science validation opportunities.

Plans to have a global series of fine-scale experiments based on regional studies during the fast sampling phase, as part of the SWOT "Adopt-a-crossover" initiative, will be presented in a companion OceanObs2019 paper by d'Ovidio et al. "Frontiers in fine scale *in-situ* studies: opportunities during the SWOT fast sampling phase."

SWOT OCEAN SCIENCE OBJECTIVES

Ocean Fine-Scales and the Energy Cascade

The primary oceanographic objective of the SWOT mission is to characterize the ocean mesoscale and submesoscale circulation determined from ocean surface topography, from the large scale down to around 15 km wavelength (Fu et al., 2012; Fu and Ubelmann, 2014). Oceanic processes at fine scales from 15 to 150 km are characterized by temporal variability of days to weeks. They crucially affect the ocean physics and ecology up to the climate scale, because of their very energetic dynamics

(Ferrari and Wunsch, 2009) creating strong gradients in ocean properties. These gradient regions act as one of the main gateways that connect the ocean upper layer to the interior (Lévy et al., 2001; Ferrari, 2011; McWilliams, 2016) and to its frontiers, including the sea-ice region (Manucharyan and Thompson, 2017) and the atmospheric boundary layer (Lehahn et al., 2014; Renault et al., 2018).

Today's gridded satellite altimetry maps have given us insight into mesoscale eddies >150 km in wavelength (Chelton et al., 2011; Morrow et al., 2018b). Yet these mapped eddies "spontaneously" appear and disappear in mid-ocean, and at present we cannot observe the smaller-scale processes that generate these larger eddies, nor their cascade down to smaller dissipative scales. In regions such as the Mediterranean Sea, with a small Rossby radius and large groundtrack separations, high-resolution modeling studies suggest we may be missing 75% of the mesoscale eddies with today's altimeter sampling (Amores et al., 2018). Although alongtrack altimetry can detect smaller SSH scales (~70 km for Jason, 30–50 km for Saral and Sentinel-3; Vergara et al., 2019), these are 1-D slices across the dynamics, and tend to observe more of the north–south SSH variability in the tropics and subtropics. SWOT's capability to observe the 2-D structure of small mesoscale processes down to 15–30 km in wavelength (i.e., eddy diameters of 7–15 km) will greatly improve our understanding of the generation and dissipation phases, and of mesoscale dynamics in small Rossby radius regions (high latitudes, regional seas, and coastal zones).

Ocean circulation models now have both the computational power and the theoretical support for simulating basin-scale regions with fine-scale resolving capabilities (e.g., Arbic et al., 2018; Qiu et al., 2018; http://meom-group.github.io/swot-natl60/science.html). Recent high-resolution modeling studies have highlighted the importance of the smaller scales generated, for example, by energetic instabilities in the deep winter mixed layers (Callies and Ferrari, 2013; Qiu et al., 2014; Sasaki et al., 2014; Chassignet and Xu, 2017). The late-winter surface relative vorticity has a myriad of small-scale structures and filaments, associated with strong vertical velocities at small-scales in the deep winter mixed layer and injection into the subsurface layers. In late summer, when the mixed layer is shallow, near-surface vertical velocities are weak, and the surface relative vorticity is at larger scales, driven by sub-surface eddies. These processes are mainly in geostrophic balance (Sasaki et al., 2014), and have a SSH signature which can be observed with conventional altimetry (Vergara et al., 2019). Since conventional 2D altimetry maps only capture scales greater than 150 km, the seasonal cycle is biased toward the summer peak, with no observations of the small-scale generating mechanisms in winter. These model results need to be validated by 2D observations which will be available from the SWOT mission.

Improving our understanding of these small mesoscale fields and submesoscale fronts and filaments is essential not only for quantifying the kinetic energy of ocean circulation, but also for the ocean uptake of heat and carbon that are key factors in climate change. Traditional altimeters combined with *in situ* data have revealed the fundamental role of larger mesoscale eddies in the horizontal transport of heat and carbon across the oceans (Dong et al., 2014). The vertical transport of heat, carbon, and nutrients is mostly accomplished by the submesoscale fronts with horizontal scales 1–50 km (e.g., Lévy et al., 2012a). The SWOT mission will open a new window for studying the SSH signature of these processes.

Balanced and Unbalanced Motions

Like other altimetric satellites, SWOT will fly at 7 km/s and cover a region of 420 km in 1 min, which will effectively provide a synoptic 'snapshot' of 2D SSH variations. The SWOT Science Team, working on the preparation of these fine-scale SSH 2D snapshots, has pushed the ocean community to re-assess their high-resolution, high-frequency ocean models and *in situ* data. Daily versus hourly averaged model outputs have a very different structure at wavelengths <200 km. Although high-frequency open ocean barotropic tides are now well estimated from models and altimetry (Stammer et al., 2014), baroclinic tides and internal gravity waves are less well known or predictable (Dushaw et al., 2011; Ray and Zaron, 2016; Zhao et al., 2016; Savage et al., 2017; Arbic et al., 2018). We have a good idea on how and where these internal tides are generated, but the location of dissipation remains a crucial question. The interaction of the internal tide with the ocean circulation and currents has been shown to be complex, with ocean currents refracting and dissipating the tide (Ponte and Klein, 2015). The dissipation of the internal tide is estimated to have an important influence on the ocean's energy budget and the mixing of water masses (e.g., Munk, 1966), but we lack observations to validate this. Improving the 2D observation of internal tides in a changing ocean stratification and inferring their lateral energy fluxes are key issues that may be addressed with SWOT. SWOT has the potential of providing the first global SSH observations of the combined balanced flow (from eddies) and the internal gravity wave field, providing new information on how they vary geographically and seasonally and how they interact.

This is a great opportunity, but is also a challenge if we want to calculate surface currents from SSH data. In contrast to the larger SSH features observed with mapped nadir altimetry, not all of the SSH fine scales from 15 to 150 km correspond to "balanced" quasi-geostrophic currents. Disentangling the contributions from the balanced eddy field and the internal tide or internal wave field will be a major challenge. The relative strength of balanced and unbalanced motion varies geographically and in time. The spatial "transition" scale at which balanced motions dominate over unbalanced motions and the seasonal patterns of their relative strength are beginning to be better understood from modeling studies and *in situ* observations (Qiu et al., 2017, 2018). These studies can provide valuable *a priori* information for disentangling balanced and unbalanced motions. Corrections are being developed for the part of the internal tide signal that is phase-locked to the astronomical tidal forcings (Zaron and Ray, 2017). *In situ* ADCP and glider measurements can also help determine the eddy-wave separation scales, following the framework given in Rainville et al. (2013) and Bühler et al. (2014). Techniques are also being explored to disentangle the signals using combined SSH and SST fields, the latter having no internal tide signal (Ponte et al., 2017). The SWOT Science Team are actively working on these questions.

SSH Wavenumber Spectra From Altimetry

The SSH wavenumber spectrum is an important indicator of ocean dynamics. Given an inertial wavenumber range, where turbulence kinetic energy is exchanged among different spatial scales through non-linear interaction, mesoscale ocean turbulence has a wavenumber spectrum of kinetic and potential energy and SSH that follows a power law. Theories predict different slopes for different dynamical regimes that govern the way energy and enstrophy are transferred among different spatial scales. For geostrophic turbulence, which occurs over scales of 10's to 100's km, the kinetic energy spectrum with respect to wavenumber, k, is proportional to k^{-3} for interior dynamics (Charney, 1971) and $k^{-5/3}$ for the surface dynamics (Blumen, 1978) or stratified turbulence (Lindborg, 2006). In accordance with the geostrophic relation, the associated SSH wavenumber spectra are k^{-5} and $k^{-11/3}$.

The SSH wavenumber spectrum has been studied since the inception of satellite altimetry. In an analysis of Seasat altimeter data, Fu (1983) showed that the SSH spectral slope is close to −5 in energetic regions and −1 in low energy regions. Even though the results were later considered to be unreliable due to the short duration of the data, the Seasat analysis demonstrated the potential utility of SSH in studying geostrophic turbulence in the ocean. Le Traon et al. (1990) analysis of 2 years of Geosat data also showed steep SSH spectra (−4 to −5) in the energetic regions and shallower spectra (−2 to −3) in low energy regions. Stammer (1997) used 3 years of TOPEX/Poseidon altimeter data to derive a −4.6 spectrum slope in mid-latitudes.

With longer satellite altimeter records, wavenumber spectral analysis has been revived with more robust statistics during the past decade. Le Traon et al. (2008) revisited the SSH spectrum using multi-mission altimetry for several energetic regions, including the Gulf Stream, the Kuroshio, and the Agulhas. They showed the SSH spectral slope to be closer to −11/3, indicating the dominance of surface dynamics. The SSH spectral wavenumber slope has a geographic dependence. For example, Xu and Fu (2011, 2012) constructed a global map using along-track Jason-1 data (**Figure 1**). The global map shows a variety of spectral slopes, without distinguishable boundaries separating different dynamic regimes. The slope is in general steeper than −2 poleward of 20°N, and shifts from −2 in low energy regions to about −4.5 in high energy regions. The fact that the steepest slopes lie between −5 and −11/3 suggests an interplay of the surface and interior dynamics.

Regardless of the exact dynamical regime, steep along-track SSH spectra in energetic regions are consistent with geostrophic turbulence over the mesoscale range (70–250 km). However, the shallower spectra in low-energy regions remain puzzling and may result from multiple processes, including direct wind forcing (Le Traon et al., 1990), or internal tides and internal waves (Richman et al., 2012; Callies and Ferrari, 2013; Dufau et al., 2016; Rocha et al., 2016; Tchilibou et al., 2018). The full 2D SSH observations of the mesoscale and internal tide/internal wave fields are needed to better understand these regional and seasonal variations.

SWOT MEASUREMENT SYSTEM

Measurement Technique, Ocean Data Products

Surface Water and Ocean Topography will use SAR-interferometric technology to observe 2D images of SSH and surface roughness over two 50-km wide swaths with a 20 km nadir gap (see **Figure 2A**). A conventional Jason-class nadir altimeter provides measurements in the central gap. SAR-interferometry has been demonstrated with SRTM on the Space Shuttle, and with Cryosat-2 SARIN mode for the polar ice caps. SWOT improves on these concepts: it is designed to have lower noise and uses different polarizations and antenna patterns to clearly distinguish the signals coming from the left-right swaths. The details of the SAR-interferometric technique are explained in Rodriguez et al. (2018).

Surface Water and Ocean Topography uses SAR processing to refine the alongtrack resolution of the return signal; the interferometric processing refines the cross-track resolution. The SWOT SAR-KaRIn instrument provides a basic measurement resolution of 2.5 m alongtrack, ranging from 70 m in the near-nadir swath to 10 m in the far swath. Over the 70% of the Earth's surface covered by oceans, SWOT's huge volume of data cannot be downloaded from the satellite. Instead, so-called "low-resolution" data will be pre-processed onboard, and building blocks of nine interferograms at 250 m posting (and 500 m resolution) will be downloaded from each antenna. Other parameters that are useful for the surface roughness and front detection, such as the 250 m resolution backscatter images, will also be downloaded. The interferometric data will be combined through a geolocation and height calculation into a 250 m × 250 m expert SSH product in swath coordinates. Most scientists will use a 2 km × 2 km product available in geographically fixed coordinates. This basic 2 km resolution product will be separated into three file types: a "light" SSH and SSH anomaly product; a wind-wave-sigma0 product; and a full SSH product with all geophysical corrections included. More details on these different data products are given at https://www.aviso.altimetry.fr/en/missions/future-missions/swot/data-products.html.

Measurement Errors, SWOT Simulator, and Effective Spatial Resolution

The SWOT SAR-interferometry measurement is designed to have small instrument noise to meet the stringent requirement of 2.7 cm in rms noise for 1 km^2 pixels. This leads to 2 cm^2/cycle/km^2 noise over the oceans at short wavelengths, for a 2 m SWH average sea-state, calculated over 7.5 km × 7.5 km averages (to resolve the 15 km Nyquist wavelength). For comparison, the noise level for the Jason series is around 100 cm^2/cyc/km^2 at 1 Hz, i.e., averaged over the 1 s oval footprint

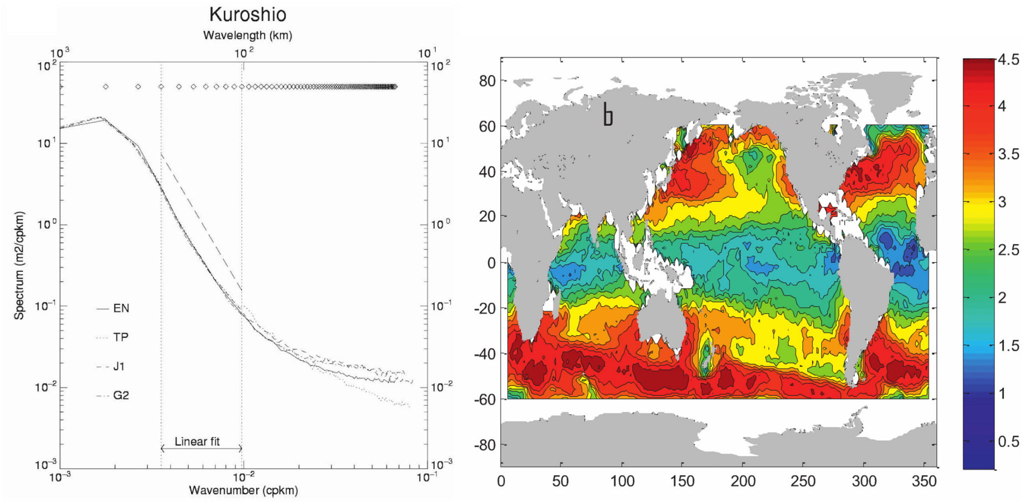

FIGURE 1 | (Left) SSH wavenumber spectra in the Kuroshio region from four altimetric missions. The –11/3 slope is shown by the dashed line (from panel b of Figure 1 in Le Traon et al., 2008). **(Right)** Global SSH wavenumber spectral slopes (with a reversed sign) in the 70–250 km range (from panel b of Figure 3 in Xu and Fu, 2012) (*copyright 2012, American Meteorological Society*).

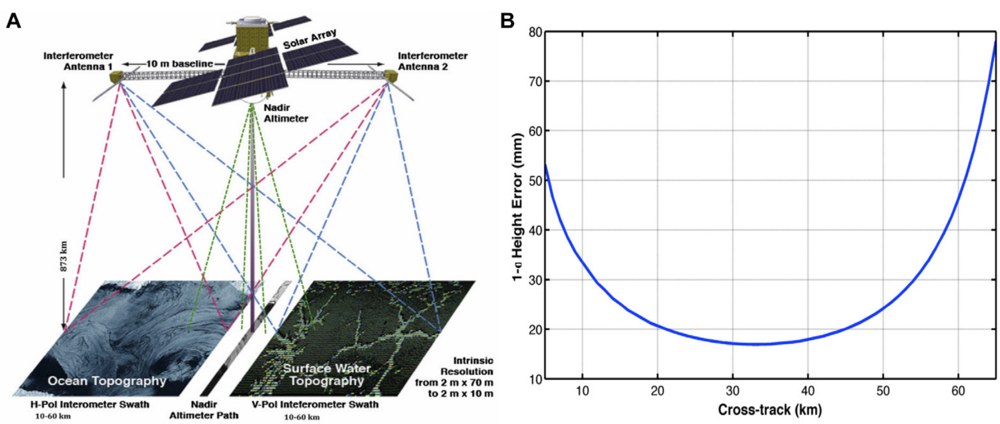

FIGURE 2 | (A) Schematic of the SWOT measurement technique using the KaRIn instrument for SAR-interferometry over the two swaths, and a Jason-class nadir altimeter in the gap. **(B)** The standard deviation of the ocean height error performance at 1 km × 1 km due to all the random errors (in mm) as a function of distance across the swath for a 2-m significant wave height. The swath-averaged (10 to 60 km) height error is 2.4 cm (*Credits: NASA-JPL*).

or roughly 100 km^2. The SWOT instrument measurement will be very precise. For the first time for an altimetric mission, the error budget is also set in terms of wavenumber, so the instrument design must meet long wavelength and short wavelength goals (see **Figure 3**). This is unprecedented for an altimeter mission. By using the wavenumber spectrum, the requirement effectively requires that the measurements be analyzed over a range of spatial scales and thus imposes a more stringent test on the satellite performance than the variance-based validation for previous altimeter missions. SWOT needs to account for standard altimetric SSH range errors, but in wavenumber space. SWOT also has specific errors associated with the interferometric calculation, including roll errors, interferometric phase and range errors, baseline errors, radial velocity errors from observing a moving target, and wave effects. The description of these errors and techniques to reduce them are detailed in the SWOT Error budget and performance document (Esteban-Fernandez, 2017) and discussed in Rodriguez et al. (2018) and Chelton et al. (2019). Most importantly, it is the random errors in the KaRIn measurements over short wavelengths that eventually determines the SWOT resolution.

Surface Water and Ocean Topography random errors across the swath are not uniform (**Figure 2B**) being larger near the edges, smaller in the center. These errors vary spatially and temporally, influenced by the surface wave and roughness conditions, as with all altimeter missions. Predictions of the SWOT sampling and noise levels are available for ocean studies using a simulator at: https://github.com/SWOTsimulator/swotsimulator.git. Since the total SWOT error has different causes and space-time structure, techniques are being developed

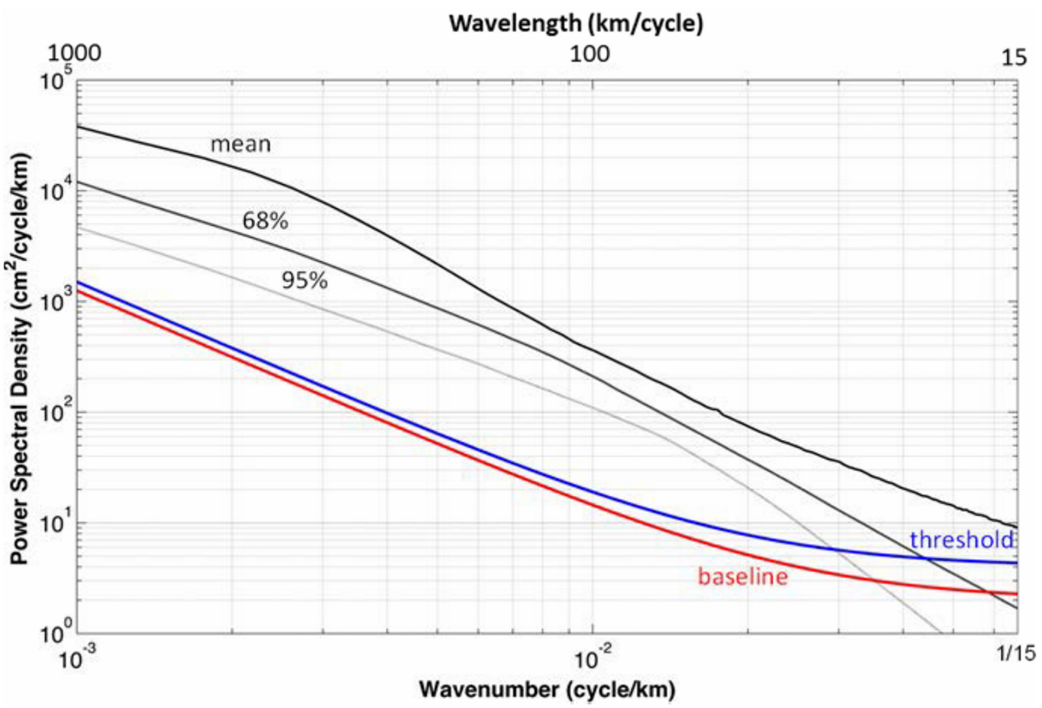

FIGURE 3 | SSH baseline requirement spectrum (red curve) as a function of wavenumber represented by an empirical function, E(k) = 2 + 0.00125 k^{-2}, where k represents along-track wavenumber. The blue curve is the threshold requirement. Shown for reference is the global mean SSH spectrum estimated from the Jason-1 and Jason-2 observations (thick black line), the lower boundary of 68% of the spectral values (the thin black line), and the lower boundary of 95% of the spectral values (the gray line). The blue and red lines represent a swath-average performance, and intersect the baseline spectrum at ∼15 km (68%) and ∼30 km (95%), respectively (Desai, 2018; *Credits: NASA-JPL*).

to estimate the noise patterns using cross-spectral methods (Ubelmann et al., 2018) and remove them using advanced de-noising techniques (e.g., Gómez-Navarro et al., 2018). This is needed since any ocean studies requiring geostrophic velocity or vorticity calculations will amplify the small-scale noise when taking the first or second derivatives of SSH.

The SWOT noise will also affect the effective spatial resolution of ocean signals, since higher noise levels will hide the smaller-scale signals. Global estimates of the SWOT noise, including a wave-dependency, have revealed the spatial distribution of this effective resolution (Dufau et al., 2016; Wang et al., 2019), i.e., the minimum spatial scale where the signal-to-noise is greater than 1. The estimated effective resolution has a geographic and seasonal dependence. It increases from about 15 km in low latitudes to ∼30–45 km in mid- and high-latitudes and is generally greater in summer than winter, but with a large geographic variation (**Figure 4**). Both eddy and internal gravity wave/tide signals contribute significantly to these scale variations. For example, in **Figure 4D**, the reversed seasonality in the southern hemisphere is due to a dominance of internal gravity waves in the subtropics in summer with low measurement noise, and dominant submesoscale energy and higher noise in winter across the Circumpolar Current. This effective resolution of the different signals and noise needs to be taken into account when combining SWOT observations with *in situ* data or models in regional analyses.

Orbits – Science Phase and Fast Sampling Phase

The SWOT launch is planned for September 2021. SWOT will spend the first 6 months in its "calibration orbit," where the satellite passes over the same site every day to calibrate the satellite parameters (groundtrack shown in **Figure 5A**). The first 3 months of this orbit are to adjust and calibrate the instrument parameters, the second 3 months (late December 2021 to late March 2022) will be available for science studies, including studies of rapidly evolving small-scale ocean dynamics. SWOT will then continue in its nominal 21-day repeat orbit for 3-years, from April 2022 to March 2025. Details of the nominal and calibration orbits in different formats can be found at: https://www.aviso.altimetry.fr/en/missions/future-missions/swot/orbit.html.

The SWOT Science Definition Team investigated the SWOT nominal orbit coverage in detail. Any orbit choice involves a tradeoff between good spatial coverage and temporal coverage. The two major communities using SWOT observations had different objectives – hydrologists needed global coverage of the smallest lakes and rivers on a monthly time scale. Oceanographers needed coverage of the small, rapidly evolving, ocean scales. The final science phase orbit covers most of the oceans up to 78°N and S (inclination of 77.6°), at 890.6 km altitude on a 21-day repeat orbit (**Figure 5C**). **Figure 5B** shows the sampling over the North Atlantic Ocean after 3-days; after

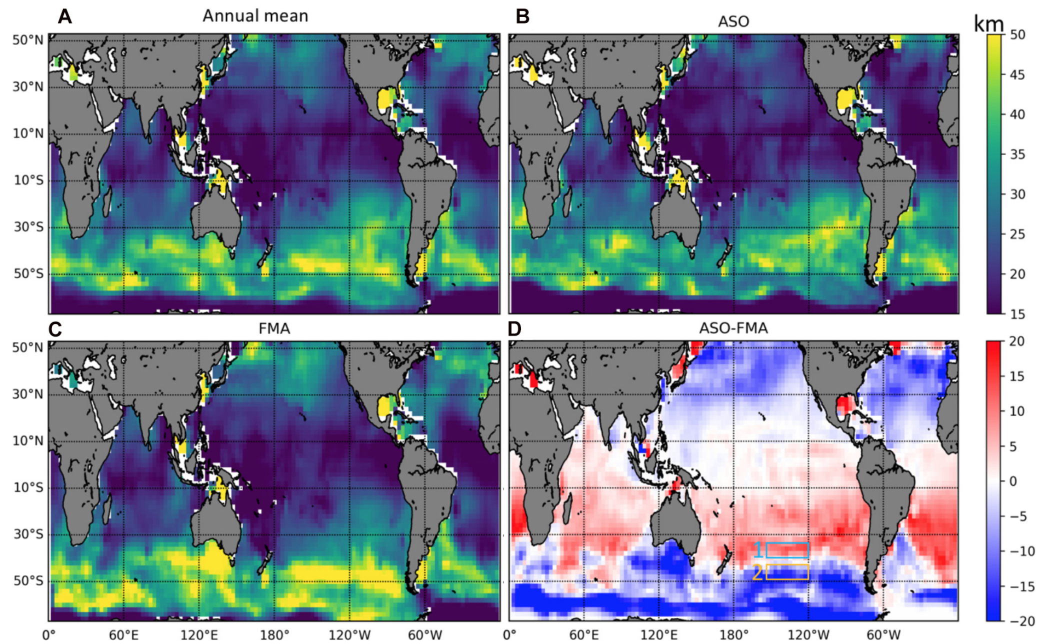

FIGURE 4 | SWOT effective spatial resolution (signal above noise) estimated from a model and simulated noise **(A)** averaged annually, **(B)** in August–September–October (ASO), **(C)** in February–March–April (FMA). The seasonal change (ASO-FMA) is shown in **(D)** (after Wang et al., 2019; *copyright 2019, American Meteorological Society*).

10-days there is loose global coverage for the mesoscales, and over the next 11–21 days the entire pattern shifts westward to fill the gaps, giving near global coverage after the full cycle (see **Figure 5C**). SWOT has a non-sun-synchronous orbit. Its inclination and repeat sampling were specifically chosen to resolve the major tidal constituents, needed to improve the coastal, high-latitude, and internal tides.

VALIDATING THE OCEAN VERTICAL CONTRIBUTION TO SWOT WAVENUMBER SPECTRA

SWOT Calibration and Validation on Wavenumber Spectrum

Calibration and validation is an important component of any satellite mission. The instrument performance can be assessed by comparing measurements to the precise ground truth. For an exploratory mission such as SWOT, CalVal is crucially important. During the CalVal phase, the SWOT orbit will be on a fast-repeat (1-day) orbit cycle, providing daily revisits along the same ground track at the expense of the spatial coverage (**Figure 5A**). Two overpasses will be made every day at the crossover locations, making these locations ideal for CalVal.

For CalVal purposes, the difference between SWOT measurements and ground truth is defined as error and specified in terms of the along-track wavenumber spectrum (**Figure 3**). SWOT measurement errors are discussed in Section "Measurement Errors, SWOT Simulator, and Effective Spatial Resolution." The requirement covers a large span of wavelengths, extending from 15 km to 1,000 km. The onboard Jason-class nadir altimeter will be used for the long wavelength CalVal (e.g., >120 km suggested by Wang and Fu, 2019). The nadir-altimeter, which benefits from the heritage and successful cross-calibration of numerous previous altimetry missions, has a well understood instrument performance and can serve as the reference for long wavelengths. Cross-calibration with other nadir missions (e.g., Sentinel-3, Jason-CS) will also be performed. The ground measurement can then focus on a smaller spatial range [15–O(100) km].

Sea surface height wavenumber spectra over 15–120 km wavelengths can be verified using airborne Lidar (e.g., Melville et al., 2016) and *in situ* observations. Unfortunately, no *in situ* observations exist today that can provide a reliable SSH wavenumber spectrum for these wavelengths. Determining the small-scale SSH wavenumber spectrum is a critical task for the SWOT *in situ* CalVal field campaign.

Due to high-frequency internal tides and waves, the construction of a ground truth that measures 15–120 km wavelengths will rely on simultaneous high-frequency (hourly at least) sampling over 120 km distance. An array of global position system (GPS) or Conductivity-Temperature-Depth (CTD) moorings is required. Wang et al. (2018) used an Observing System Simulation Experiment (OSSE) to demonstrate the ability of moorings to meet the requirement. The GPS's capability is undergoing testing near the Harvest platform at the time of writing.

Global position system measures the true ocean surface height as seen by satellite, while the SSH reconstruction by

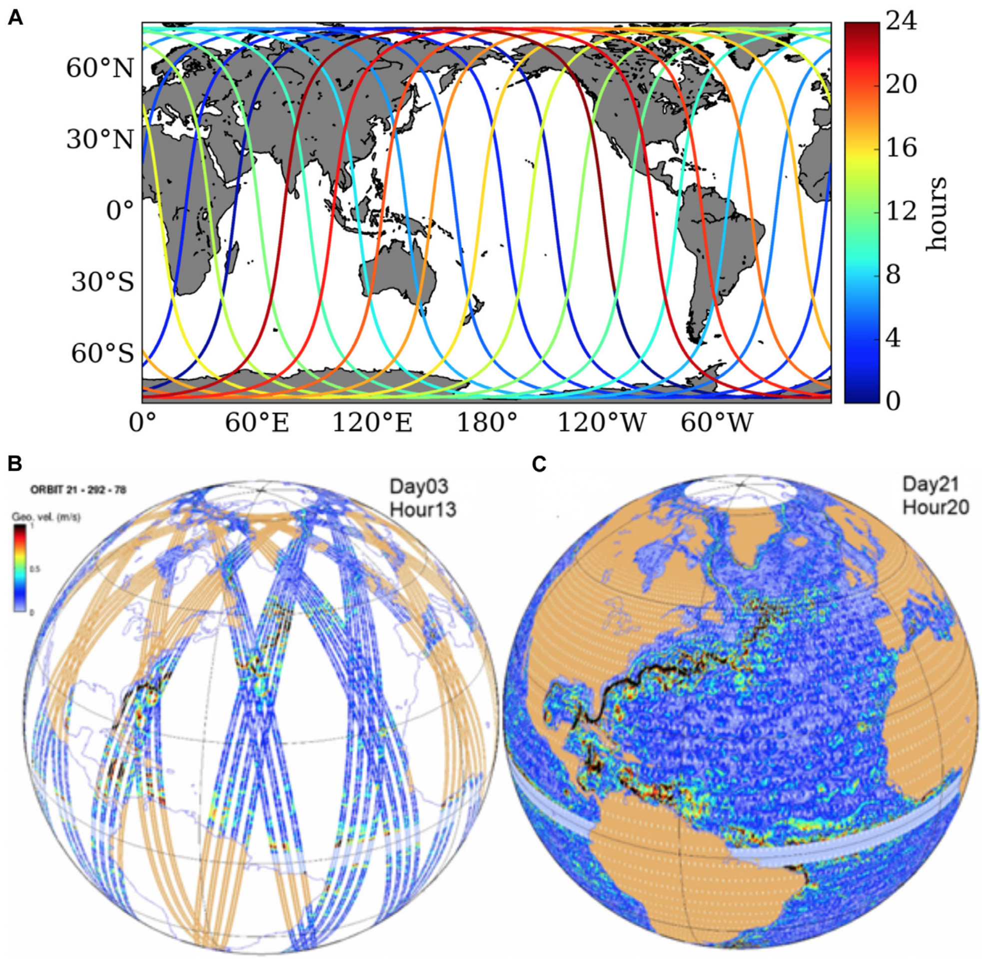

FIGURE 5 | (A) Global coverage of SWOT's 1-day orbit. Color shows the time in hours of each pass (Wang et al., 2018) © Copyright [2018] American Meteorological Society (AMS). SWOT coverage in its 21-day orbit after 3 days **(B)** and 21 days **(C)**. The color shows model simulations of SSH at the measurement time (after Morrow et al., 2018a; *copyright 2018*, *CreateSpace Independent Publishing Platform*).

CTD moorings relates to the ocean dynamic topography, the component that is meaningful for studying ocean circulation. GPS can be referred to as a direct *geodetic validation,* and CTD moorings are an indirect *oceanographic validation*. The primary oceanographic objectives of the SWOT mission are "to characterize the ocean mesoscale and submesoscale circulation determined from the ocean surface topography at spatial resolutions of 15 km (for 68% of the ocean)" (Fu et al., 2012). It is important to have both geodetic and oceanographic components evaluated at the CalVal site simultaneously in order to connect the satellite measurements with the interior ocean physics.

SWOT Validation Using *in situ* Observations

The SSH, η, is related to three dynamical terms through the hydrostatic equation:

$$\eta = \frac{p_b^{'}}{\rho_0 g} - \frac{p_a}{\rho_0 g} - \int_{-H}^{0} \frac{\rho^{'}}{\rho_0} dz \qquad (1)$$

where p_a is the surface atmospheric pressure loading, p_b the bottom pressure and $p_b^{'} \cong p_b - p_0 gH$ the bottom pressure anomaly. The term $\int_0^{\eta} \frac{\rho^1}{\rho_0} dz$ has been neglected because $\eta << H$ in the open ocean. In real satellite measurements, additional terms due to the geoid, measurement errors, and noise will appear on the right-hand side of the equation but are dynamically irrelevant and often corrected. The atmospheric loading, i.e., the inverted barometer response (Doodson, 1924), is routinely corrected using atmospheric reanalysis. Barotropic signals appear in the bottom pressure and are believed to have large spatial scales, greater than 120 km in wavelength in the open ocean. The third term, the steric height (or dynamic height with a factor of g difference), reflects ocean interior dynamics and is the most important variable for altimetric oceanography.

In situ oceanographic validation means that we need to compare the satellite measurement to the dynamic height reconstructed from the hydrographic measurements and understand their connection in terms of spatial structures such as wavenumber spectrum.

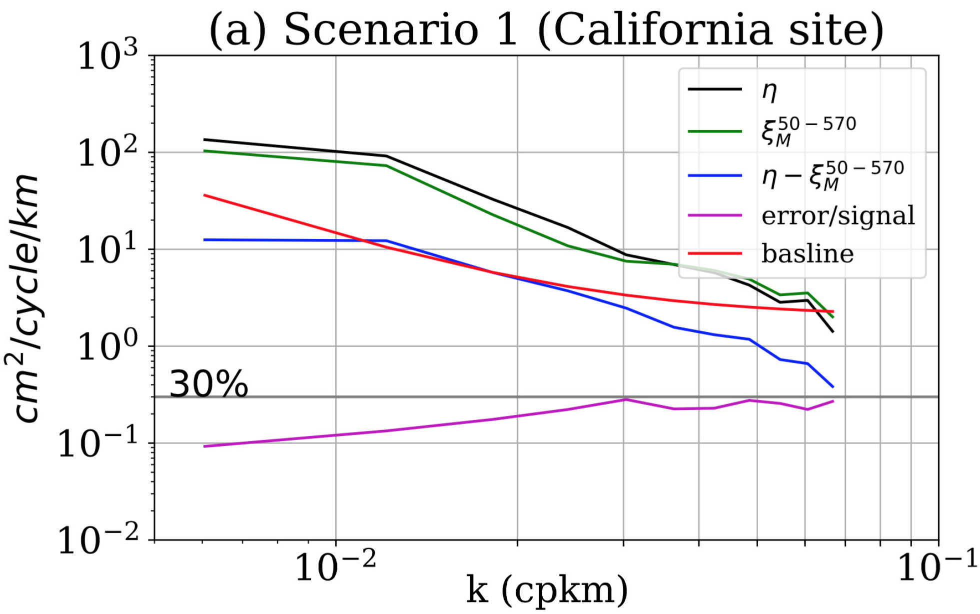

FIGURE 6 | The wavenumber power spectrum density of the true SSH anomaly η (black), the mooring reconstruction ξ_M (green), the residual $\eta - \xi_M$ (blue), the error-to-signal ratio (purple), and the baseline (red). Visual guide of the 30% (0.3) level (horizontal line) (Wang et al., 2018; *copyright 2018, American Meteorological Society*).

The CalVal Site Near California

Among the 14 crossover locations in mid-latitudes (~35°N), the one in the California Current System (CCS) about 300 km off Monterey has been proposed as the main SWOT CalVal site (125.4W, 35.7N). This location belongs to a family of oceanic eastern boundary currents. The CCS is one of the most well studied boundary currents due to its socio-economic importance. The first concentrated investigation of this region dates back to 1937 (Sverdrup and Fleming, 1941).

Dynamic height has long been used to study the circulation of the CCS (e.g., Sverdrup and Fleming, 1941; Reid, 1961; Wyllie, 1966). One particular example is Bernstein et al. (1977), who studied California Current eddy formation using dynamic height calculated from California Cooperative Oceanic Fisheries Investigations (CalCOFI) observations and satellite images. The dynamic height used in that study was based on hydrographic profiles of the upper 500 m. Results showed good agreement between the circulation pattern in the 500 m-dynamic height and the mesoscale eddies identified in satellite infrared imageries. Since then, numerous field programs have taken advantage of the abundance of both *in situ* observations and higher resolution satellite measurements (e.g., Brink and Cowles, 1991).

Hydrographic profiles from the upper 500 m have been widely used for dynamic height calculations and may well account for the majority of the total variability, but we do not yet know whether they are sufficient to meet the SWOT requirement. Deep eddies have been observed occasionally (Collins et al., 2013). In addition, high-frequency internal tides and waves may have deep-reaching structure. The combination of deep-reaching dynamics, the large span of the spatial scales, and the fast-changing waves impose significant challenges for validating the SWOT SSH snapshots.

Wang et al. (2018) OSSE used a high-resolution (1/48° in horizontal and 90 levels in vertical) global ocean simulation with tidal forcing, and analyzed the contribution of upper-ocean density variations to the SSH wavenumber spectrum. They showed that the upper 570 m accounts for more than 70% of the variance of SSH for all wavelengths between 15 and 150 km near the CalVal site in CCS. The remaining 30% variance not captured by the upper ocean does not result in an error exceeding the SWOT baseline requirement. The results in wavenumber space are shown in **Figure 6**, where the error (blue lines), defined as the difference between the model SSH and the dynamic height calculated from the 570 m synthetic mooring observations, is near or below the SWOT baseline requirement. Observing the deeper ocean leads to a better reconstruction of the truth (not shown). Sampling the upper 570 m of the ocean was a compromise of cost versus performance based on a preliminary study. The design of the *in situ* CalVal system has been evolving, leading to a new plan of using full-depth moorings of sensors to reach over 90% accuracy.

In summary, the stringent SWOT science requirement on the SSH wavenumber spectrum requires a comprehensive *in situ* field program for CalVal. This will provide an opportunity to build a larger oceanography science field campaign by taking advantage of both the large SWOT CalVal instrument array and the simultaneous SWOT swath SSH measurement. The expanded field program, in turn, will enhance our understanding of the future SWOT data and their connection to ocean dynamics.

As mentioned in the introduction, other science validation studies are planned during the fast sampling phase in different dynamical regimes in both hemispheres, so in different seasons. These are described in more detail in the accompanying OceanObs review paper "Resolving the fine scales in space and time: interdisciplinary science opportunity during the SWOT fast sampling phase and beyond."

OPPORTUNITIES FOR MULTI-SATELLITE SURFACE CHARACTERISTICS OF FINE-SCALE FRONTS AND EDDIES

Frontal Signatures in Optical and Radar Data

Satellite optical and radar measurements often reveal sea surface roughness changes at sub-kilometer scales, mostly under low to moderate wind conditions (e.g., Alpers, 1985; Yoder et al., 1994). These surface roughness changes can be traced by surface current gradients, related to internal waves and/or surfactant lines created by surface velocity convergences. They typically occur with sharp gradients of temperature and/or ocean color. Efforts have been made to interpret surface roughness gradients quantitatively (e.g., Kudryavtsev et al., 2014; Rascle et al., 2016, 2017). They confirm that horizontal convergence and shear estimated from *in situ* drifters are generally consistent with the theoretical wave action equation (e.g., Kudryavtsev et al., 2005, 2012). This equation predicts how current gradients influence the amplitude of short gravity waves that propagate in different directions, from which a surface optical reflectance or radar cross section can be estimated. When several viewing angles are available, optical or radar measurements can be inverted to yield both the amplitude and direction of the surface current gradient.

Surface Water and Ocean Topography backscatter variations will be released on a 250-m resolution grid, as discussed in Section "SWOT Measurement System," and are expected to provide a more nuanced view of frontal scale variations than will be available from the processed SSH data (**Figure 7**). To leading order, backscatter variations will inform us about local changes related to the omni-directional short scale mean squared slopes. As anticipated [e.g., Eq. (3) in Kudryavtsev et al., 2012], this can offer a direct link between SWOT's SSH mapping capabilities and the divergence/convergence of the sea surface current field. We expect that SWOT's combined measurements (SSH, surface wave mean squared slopes) will thus offer an unprecedented capability to trace intense cross-frontal dynamics and vertical motions, including spiraling eddies (Munk et al., 2000; Eldevik and Dysthe, 2002), internal waves and cold-filaments (McWilliams et al., 2009).

Sea State Modification Across Fronts and Eddies – Today and With SWOT: Issues and Opportunities

Winds over the ocean can be gusty, with intermittent features and small-scale spatial variations that modulate larger-scale patterns of variability. If winds move at the same velocity as ocean currents, they have no net impact on the ocean surface: the net wind-stress exerted by the wind on the ocean depends on the differential velocity between the wind flow at the surface and the ocean currents just below (e.g., Liu et al., 1979; Kelly et al., 2005). Wind stress can generate surface waves, which propagate horizontally through the ocean, modulated by ocean currents (e.g., Ardhuin et al., 2017). Some of the energy input to the ocean by the wind drives the large-scale ocean circulation; some energy is dissipated within the wave field or through breaking along the shore and has little net impact on the large-scale ocean circulation. One of the critical questions for physical oceanography has been to understand the interactions of winds with waves and small-scale ocean currents. SWOT's resolution of the backscatter associated with the wave field and its sea surface height measurements will offer valuable contributions to the study of wave–current interactions, and the addition of separate satellite missions to measure currents, waves, and wind will enable more detailed assessment of the mechanisms driving wind power input to the ocean.

Whereas the surface roughness is defined by short gravity waves (wavelengths around 1 m) with variations of the order of 10% due to currents, the effect of currents on dominant wind-waves can be much larger (Kenyon, 1971; Romero et al., 2017). Even in the absence of non-linearities, waves traveling through a field of varying surface currents can exhibit random focusing, possibly leading to extremely high wave intensification (e.g., Kudryavtsev et al., 2017; Quilfen et al., 2018). Such an effect is generally non-localized with the surface current changes, but is related to the ratio between surface current gradient (vorticity) and wave group velocity. From the conservation of action, the spatial variability of the significant wave height (SWH) will thus be linked to the surface kinetic energy of the current (Ardhuin et al., 2017). This variability of SWH can be a source of noise in the SSH estimation, through the sea-state bias estimation. It is also an opportunity to better characterize small scale currents, provided that the SWH (from the nadir instrument, and very near nadir estimates) or other estimated sea state parameters are available (Quilfen et al., 2018). Also, building on the long-range propagation of ocean swells (Collard et al., 2009), there is a great potential to assess refraction effects estimated from SWOT's 2D wave-mapping capabilities, in order to improve wave forecasts and comparisons with other (satellite, *in situ*) sea state measurements.

The China-France Oceanography Satellite (CFOSAT), which will measure winds and waves starting in 2018, as well as proposed satellites, including the European Space Agency's Sea surface Kinematics Multiscale monitoring (SKIM) mission and a NASA concept for a Winds and Currents Mission (WaCM), all offer the potential to complement SWOT with coincident measurements of surface currents plus waves and/or winds. Aircraft measurements from Lidar, and from the airborne version of SWOT – AirSWOT, and from DopplerScat, a suborbital WaCM prototype, have all demonstrated the alignment of winds and currents. SWOT's high-resolution Doppler Centroid product, in combination with microwave-derived wind, wave, and current measurements from Lidar, CFOSAT, SKIM, and/or

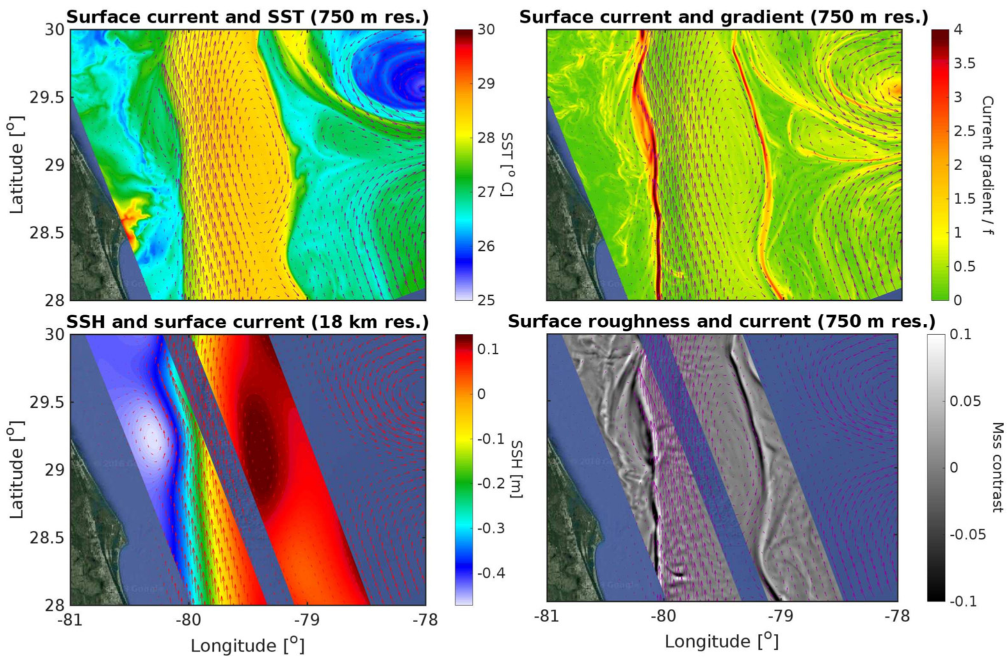

FIGURE 7 | Numerical simulations over the Gulf Stream to illustrate the possible synergetic use of SWOT SSH (averaged at 18 km, bottom left) and SWOT backscatter (averaged at 750 m, bottom right). Geostrophy at 18 km resolution does not reproduce frontal structures (bottom left, red arrows), with weak current gradients, always well below the Coriolis frequency f (not shown). The backscatter at sub-kilometer resolution (bottom right) provides information on the location and amplitude of the intense current gradients (top right) (*Credits: Ifremer*).

WaCM have the potential to highlight the fine-scale wind–wave–current interactions through which momentum is transferred between the atmosphere and the ocean.

Fronts, Ocean Color, and Structuring Biomass

Ocean fronts can be characterized by strong vertical velocities, in addition to supporting sharp gradients in temperature, current speed and other ocean properties. The vertical velocities at fronts can bring nutrients to the ocean surface and stimulate primary production, and play an important role in marine ecosystems. Ocean color data highlight the filamented structures of chlorophyll-a at the ocean surface (e.g., Kahru et al., 2007), which can be extremely narrow, suggesting the importance of both horizontal and vertical velocities in governing biological productivity at scales smaller than the eddy scale: the sub-mesoscale (Lévy et al., 2001, 2012b; Mahadevan, 2016), with possible effects propagating to higher trophic levels (Lehahn et al., 2018). However, the data to analyze these processes have not been available in a consistent global form. Ocean color data and high-resolution SST are not available in cloudy conditions, and therefore both are highly patchy, SAR imagery is not archived globally, and other sensors have not achieved high-resolution sampling in two dimensions. SWOT's global swath sampling, particularly if used in combination with other sensors, will provide a means to assess the structure of waves and SSH gradients at ocean fronts in the context of chlorophyll-a color measurements.

FROM SWOT OBSERVATIONS TO 2D SSH AND 3D FIELDS

Improved 2D Mapping of Fine-Scale SSH With SWOT and Nadir Altimeters

Present-day 2D maps of SSH, derived from a constellation of two to five nadir altimeters using statistical, static interpolation techniques (Dibarboure et al., 2011), do not resolve scales smaller than 150–200 km in the mid latitudes. SWOT will provide an unprecedented opportunity to increase spatial resolution, but the mapping method must be adapted. Due to the mismatch between spatial and temporal coverage of SWOT, fast and small-scale dynamical processes may develop and move unobserved between two passes, possibly leading to a poor mapping of SSH. This is suggested by **Figure 8**, showing that ocean decorrelation times decreases dramatically as the spatial scales decrease. At 180 km, the decorrelation time is about 10 days which is the typical revisit of nadir altimetry. However, at 15 km, the decorrelation time is below 1 day, much shorter than the revisit of SWOT. For this reason, temporal interpolation in mapped SSH data should be revisited, from a static statistical approach to a dynamical approach, to better represent the small scales' evolution.

A proof-of-concept study of dynamical interpolation has been carried out by Ubelmann et al. (2015), quantifying the improvements in the reconstruction 2D of SSH fields with a 1-layer Quasi-Geostrophic model relying on a single parameter: the Rossby radius. The simulated results suggest significant improvements (up to 30% error reduction and 20%

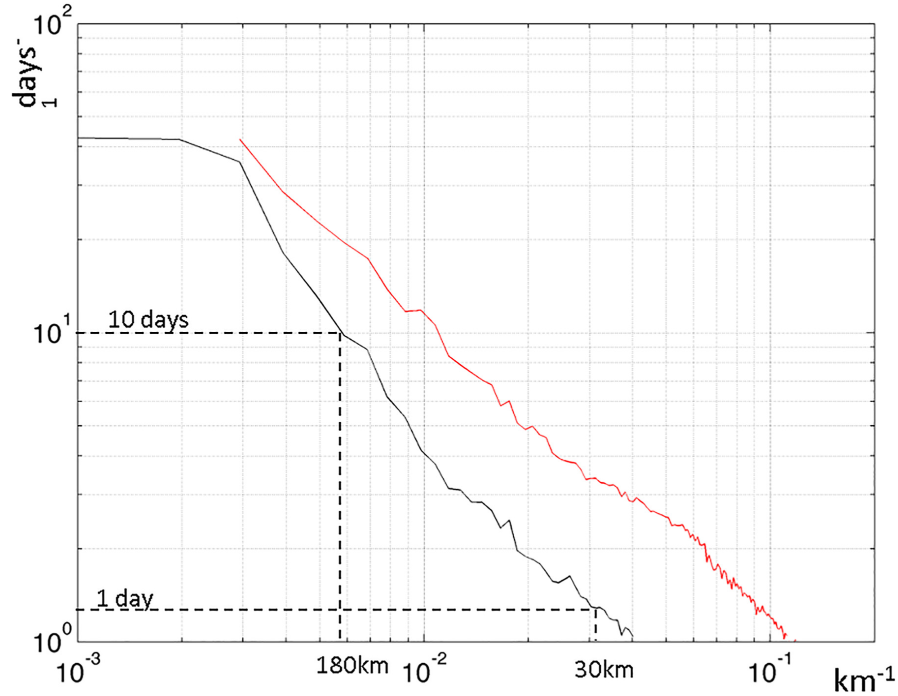

FIGURE 8 | Black curve: decorrelation time as a function of wavelength (shown in inverse log scale, per day and/km, respectively) estimated from an MITgcm simulation in the North Atlantic. Red curve: Decorrelation time when we subtract the 1-layer Quasi-Geostrophic evolution (*Credits: NASA-JPL*).

gain in resolution) in energetic western boundary currents. Ubelmann et al. (2016) implemented the method to use simulated observations. **Figure 9** illustrates the results with simulated SWOT data. The limitation of the statistical interpolation technique, and the benefits of a dynamical approach are clear on this image: Two well-defined eddies are detected by SWOT at two different times separated by 7 days (top panel). They have moved during this period. The SSH field estimated at an intermediate time using the statistical interpolation technique shows sluggish, deformed eddies (bottom panel, center), since they result from a weighted average of the two initial images. The eddies' integrity is much better represented using a dynamical interpolation technique (bottom panel, right).

Another dynamical approach where the time interpolation relies upon quasi-geostrophic dynamics is also explored, where simulated SWOT observations are combined with the model through a back-and-forth nudging approach (Auroux and Blum, 2008; Ruggiero et al., 2015): the model is iteratively run forward and backward over a fixed time window, and gently nudged toward the observations at every time step with an elastic restoring force. Results indicate that this approach successfully reconstructs the SSH field in the full space and time domain considered.

Efforts are continuing to investigate dynamical mapping strategies to draw the maximum benefits from SWOT and alongtrack altimetry's fine-scale SSH. Approaches reported here are encouraging, but have been explored by ignoring or minimizing the structured component of SWOT errors (roll, baseline, phase and range errors in particular). Dealing with such errors is part of ongoing work, and a major challenge for the inclusion of SWOT in the 2D mapping of SSH.

3D Projection From Surface Satellite SSH and SST/Density Observations

Surface Water and Ocean Topography sea level provides an estimate of pressure at the ocean surface which may be extrapolated downward in the water column and provide an estimate of the circulation at depth. Assimilation of SWOT and other available data with realistic 3D primitive equations numerical models may achieve this albeit at a large computational cost (see section "Assimilation of SWOT Data").

For the larger mesoscales, empirical statistical correlations have been developed between altimetric sea level observations and collocated Argo dynamic height at depth (Guinehut et al., 2006, 2012). Owing to the geostrophic relationship between currents and pressure, the observed low modal vertical structure of currents may be leveraged to extrapolate sea level downward (Wunsch, 1997; Sanchez de La Lama et al., 2016), and the resulting vertical structure may be justified dynamically (Smith and Vallis, 2001). We still need to explore how these approaches extend to the newly resolved 2D scales of SWOT.

Other approaches have relied on quasi-geostrophy which is the relevant dynamical framework for mesoscale motions. At mesoscales, primitive equations (for velocity, temperature, salinity, etc.) can indeed be recast in a simpler system where the only state variable is potential vorticity (PV), which binds fluctuations of currents and density. Previous studies

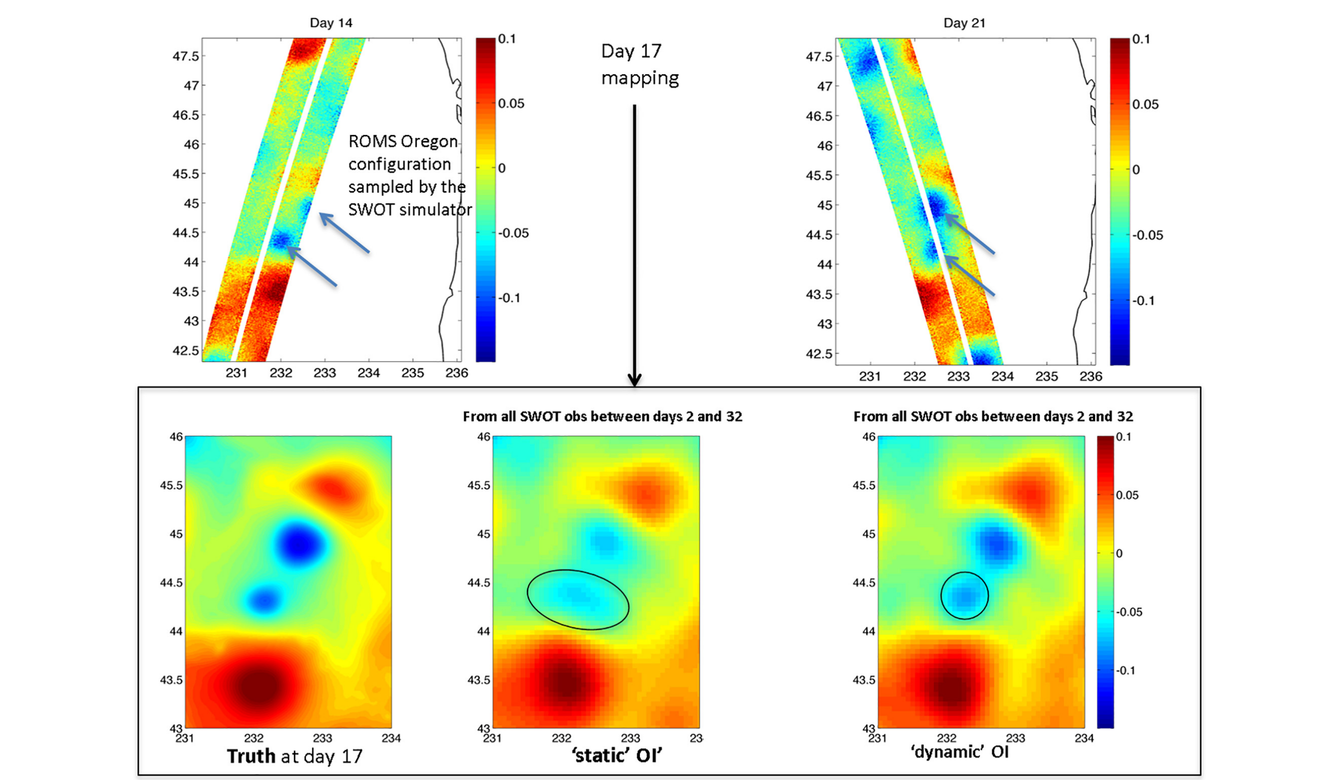

FIGURE 9 | Upper panels: SWOT Level 3 data shown for day 14 and day 21 in a simulation off the Oregon coast. Lower panels: from left to right: reference field, analyzed field with static optimal interpolation and analyzed field with dynamic interpolation on day 17, processing all data available between days 7 and 27 (*Credits: NASA-JPL*).

have reconstructed 3D fields from a combination of *in situ* and satellite observations, including the estimation of vertical velocities, through the quasi-geostrophic approximation (Ruiz et al., 2009; Buongiorno Nardelli et al., 2012; Pascual et al., 2015; Mason et al., 2017; Barceló-Llull et al., 2018). A key problem when trying to obtain accurate estimates of the vertical exchanges from *in situ* and remote sensing data is related to the availability of high-resolution data. In this context, SWOT will make an unprecedented contribution when combined with *in situ* observations.

Assuming specific relationships between SSH, SST and PV, different studies have shown the feasibility of inverting oceanic currents in 3D from these surface observations in both idealized and realistic settings (Lapeyre and Klein, 2006; Klein et al., 2009; Ponte and Klein, 2013; Wang et al., 2013; Qiu et al., 2016) (**Figure 10**). Further theoretical advances are needed to account for vertical variations of PV that are not directly related to surface variables (Lapeyre, 2009; Fresnay et al., 2018). As for the 2D mapping of SWOT data (see section "Improved 2D Mapping of Fine-Scale SSH With SWOT and Nadir Altimeters"), using the predictive nature of quasi-geostrophy may also allow progress in the future.

Many of the outstanding issues and opportunities (3D circulation reconstruction, balanced/internal wave disentanglement) will require that we combine SWOT sea level observations with other types of observations. Statistical approaches show that the combination of sea surface temperature observations with sea level can improve reconstructions of 3D pressure and currents at mesoscales (Mulet et al., 2012). Surface tracers which have been stirred by advective currents have been used to improve finer-scale surface current estimates (Rio et al., 2016) or to disentangle internal waves from balanced contributions to sea level (Ponte et al., 2017). Much remains to be investigated about the relevant observations needed, as well as the development and performance assessment of methods for propagating SWOT observations into the ocean interior, via statistics, dynamics or both.

Assimilation of SWOT Data

Surface Water and Ocean Topography will provide very high resolution observations along its swaths but will not be able to observe the evolution of the high frequency signals (periods < 20 days). The assimilation of SWOT data in ocean models will be instrumental to control smaller scales (<100 km) that are not well constrained by conventional altimeters. The most impacted fields will be surface and intermediate horizontal velocities, which directly impact on key applications such as marine safety, pollution monitoring, ship routing, and the offshore industry. A better constraint on vertical velocities will also directly impact biogeochemical applications.

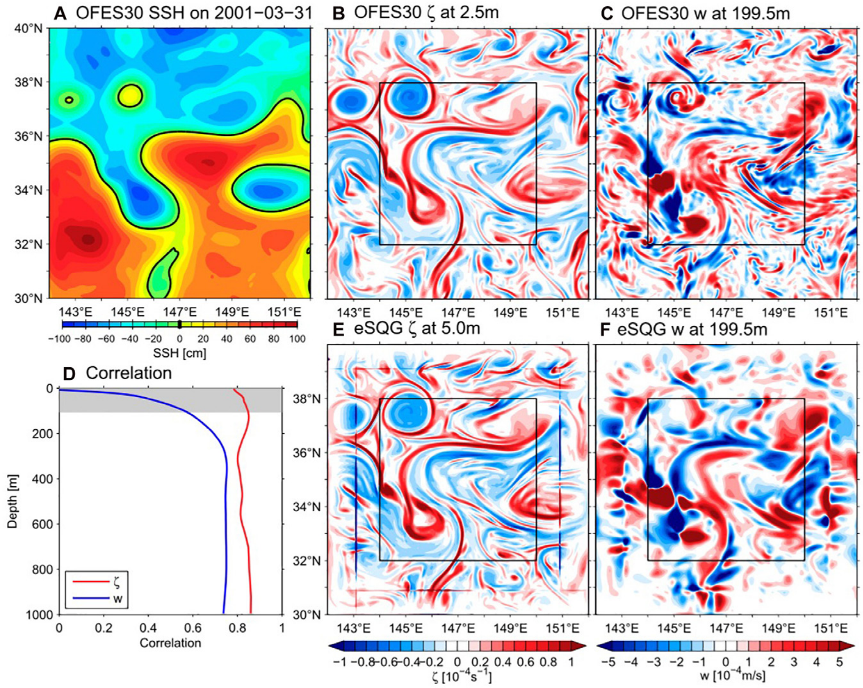

FIGURE 10 | (A) Numerical simulation sea level on March 31, 2001. **(B)** Relative vorticity at 2.5 m and **(C)** vertical velocity w at 199.5 m from the numerical simulation. **(E)** Relative vorticity at 5.0 m and **(F)** w at 199.5 m reconstructed based on sea level according to effective SQG. **(D)** Linear correlation coefficients for relative vorticity (red line) and w (blue line) between the original and reconstructed fields as a function of depth. Gray shade denotes the mixed layer depth averaged in the reconstruction region of 32°–38°N and 144°–150°E (see Qiu et al., 2016 for details; *copyright 2016, American Meteorological Society*).

The challenge of assimilating SWOT is multi-facetted. We can identify four conditions to be fulfilled to draw maximum benefit from SWOT data assimilation:

(i) The assimilative model should have a spatial resolution comparable to SWOT. This is by itself a big challenge: running a basin-scale model at SWOT resolution on present-day supercomputers is computationally extremely expensive. Computational complexity issues are further aggravated in data assimilation mode.
(ii) The model should represent all the physical processes affecting SWOT data. As mentioned earlier, dealing with internal tides in SWOT data is a particularly difficult and open question. Internal tides are even more challenging for SWOT assimilation since their signature on SSH can exhibit long spatial coherence, whereas some assimilation methods work under the assumption that observations have a local signature only.
(iii) SWOT's temporal coverage should fit the characteristic time scales of the model's dynamics, yet this will not be the case. To draw maximum benefit from SWOT's spatial resolution while minimizing the adverse effects of its temporal resolution, SWOT data will have to be assimilated in combination with conventional along-track altimeters and *in situ* observations (e.g., Argo).
(iv) SWOT data should be integrally assimilated. It is common, when dense data are assimilated, to thin the observation data set. A main objective of data thinning is to avoid data with correlated errors, simply because data assimilation systems are not designed for such data.

Different groups in the SWOT Science Team are working on these issues. To address (i) and (ii) above, the approach followed by Mercator Ocean is to develop/test innovative data assimilation methods and analyze the impact of simulated SWOT data through OSSEs. The long term plan is to ingest SWOT data in near real time (<2 days) in the operational Mercator Ocean and Copernicus Marine Service global and regional data assimilation systems. First OSSEs in the North East Atlantic have been carried out with a 1/12° (assimilated run) and a 1/36° (nature run) North Atlantic regional models that include tides. SWOT data were simulated using the SWOT ocean simulator (see section "Measurement Errors, SWOT Simulator, and Effective Spatial Resolution"). Several experiments have been made using the new R&D versions of the Mercator Ocean assimilation scheme (SAM-2) (e.g., 4D scheme) and the latest version of the NEMO model code. Our initial results demonstrate the high potential of SWOT observations to constrain ocean analysis and forecasting systems (**Figure 11**).

Methods to deal with spatially correlated errors in SWOT [challenge (iv) above] have been developed by Ruggiero et al. (2016) and Yaremchuk et al. (2018). The common strategy consists of assimilating spatial derivatives of SWOT (along and across-track, first and second order) in addition to the original SWOT data itself. This is equivalent to

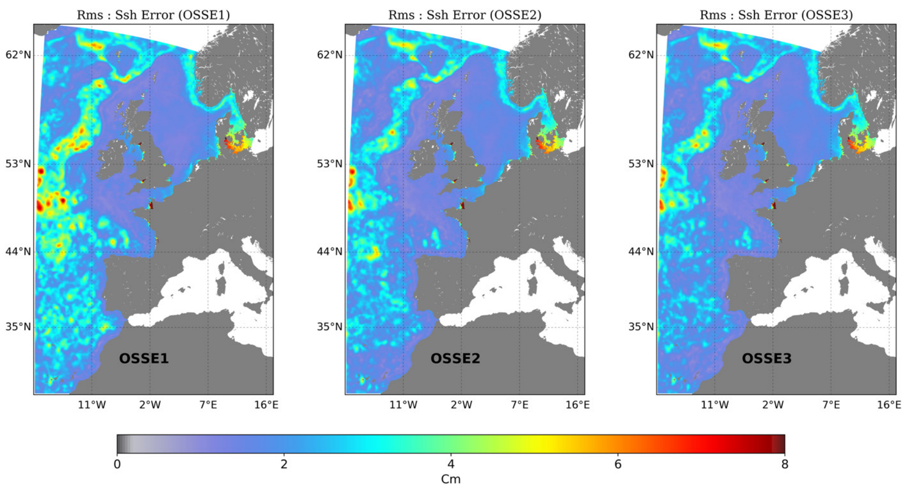

FIGURE 11 | Map of the SSH analysis rms error over the IBI domain during 2009 (in cm). Results were obtained by comparing the analyzed SSH in the experiments OSSE1 (three nadir altimeters), OSSE2 (SWOT), and OSSE3 (SWOT + three nadir altimeters) with the data of the NatRun (*Credits: Mercator Ocean*).

assimilating SWOT data alone with a certain type of error correlation. The observation data set increases by a factor close to 5, but the assimilation can be performed assuming present-day assimilation tools. Ruggiero et al.'s (2016) study makes use of simulated SWOT data with degraded resolution; the next challenge is to move toward full resolution. Yaremchuk et al.'s (2018) method has not been tested yet in assimilation mode.

FINE-SCALE SWOT 2D SSH AND *in situ* DATA FOR OBSERVING 4D OCEAN DYNAMICS

Surface Water and Ocean Topography will provide an exciting new view of the dynamic pressure field of the upper ocean, with unprecedented spatial resolution and coverage. This new window into ocean variability at wavelengths of 15–150 km will raise many new questions about ocean dynamics at these scales. Indeed, even the prospect of SWOT's new measurements has stimulated many fundamental questions about the contributions of balanced and unbalanced dynamics to SSH variability (see section "Balanced and Unbalanced Motions"), the interpretation of SSH wavenumber spectra (see section SSH Wavenumber Spectra From Altimetry"), the small-scale structure of the marine geoid, approaches to *in situ* CalVal (see sections "SWOT Calibration and Validation on Wavenumber Spectrum," "SWOT Validation Using *in situ* Observations," and "The CalVal Site Near California"), and approaches to exploit the SWOT data to make inferences about the 3D flow field (see section "3D Projection From Surface Satellite SSH and SST/Density Observations"). Many of these questions are difficult to answer because they involve not only the 2D information that SWOT will provide, but also require more information than is currently available about the full spectrum of ocean variability in three spatial dimensions and time. In addition, the relationship between surface pressure fluctuations (SSH anomalies) and the many other dynamical quantities of interest (particularly horizontal and vertical velocity and property fluxes) is itself complicated at wavelengths below 150 km. SWOT data alone will not fully address the many pressing scientific questions concerning ocean variability at horizontal wavelengths below 150 km, but there are exciting opportunities to make advances on these questions by combining SWOT data with other measurements.

Over the last 25 years, many studies have analyzed the larger scale ocean dynamics using a combination of satellite altimetry and collocated *in situ* observations. Moorings have been aligned along altimetry groundtracks to study full-depth ocean transport and larger mesoscale variability, for example in the Kuroshio Current (Imawaki et al., 2001; Andres et al., 2008), across Drake Passage (Ferrari et al., 2013) or in the Agulhas Current (Beal et al., 2015). These moorings were generally spaced 1–2° apart, resolving only the larger-scale circulation. Gliders and ship-ADCP sections have been collocated with altimetric groundtracks (Heslop et al., 2017; Morrow et al., 2017), but these observations take days to cover hundreds of km, compared to altimetric observations in 30 s. In regions with rapidly moving dynamics, only small sections remain collocated. Dedicated *in situ* campaigns have provided insight at local sites into these rapidly evolving submesoscale dynamics at scales less than 15 km (e.g., OSMOSIS – Buckingham et al., 2016) or with campaigns that moved with energetic frontal features (e.g., LATMIX – Shcherbina et al., 2015). Specific campaigns have also investigated local internal wave dynamics (e.g., IWEX – Briscoe, 1975; Ocean Storms – D'Asaro et al., 1995), including with glider sections (Rainville et al., 2013). However, it remains a major observational challenge to resolve the 15–100 km ocean fine scales in time, depth, and the two horizontal dimensions, especially because internal tides and internal gravity waves require temporal sampling on the order of an 1 h.

A recent community workshop (held in Crystal City, VA, United States from 4 to 5 October 2018) focused on how the launch of SWOT and the activities occurring around it present opportunities for major advances in quantitative understanding of the dynamics of mesoscale, submesoscale, and internal-wave variability. The group of about 40 in-person and remote attendees discussed organizing one or more field campaigns, coordinated with SWOT satellite and cal/val measurements, to allow significant advances on the important science questions that motivated the SWOT mission. The NASA Sub-Mesoscale Ocean Dynamics Experiment (S-MODE) will include extensive measurements from aircraft, research vessels, and autonomous platforms in the SWOT CalVal region off of California during 2020–2021, and it presents another opportunity that can be leveraged toward a more complete understanding of the dynamics at scales below 150 km. By the end of the 2-day workshop, the group had identified a few important actions: (1) supporting the Adopt-a-Crossover effort being organized as a PI-driven effort to collect measurements in crossovers of the SWOT fast-repeat orbit, (2) organizing some additional measurements in the California Current region to complement the SWOT fast-repeat measurements, the SWOT CalVal array, and S-MODE measurements to make it possible to resolve the 4D ocean variability at a level of detail that has never been possible, and (3) to have a separate, dedicated SWOT field campaign in the Gulf Stream region 1–2 years after the SWOT launch. This third activity would have its primary scientific focus on the small mesoscales that SWOT would resolve, and it would take place during the 'science orbit' phase of SWOT (not the fast-repeat orbit) to allow the scientific community time to better assess and understand the SWOT data before trying to execute an *in situ* campaign intended to allow better use of the SWOT data.

FUTURE, FORWARD VISION

Years before the SWOT launch, the promise of observing a new 2D SSH field over scales from 15 to 150 km is opening new research domains. Exciting questions are being explored on the role of small mesoscale and sub-mesoscale dynamics in the ocean circulation, and their impact on the energy budget, on mixing and dissipation, on the generation of larger-scale dynamics, and on the vertical exchange between the surface and deeper layers. Improving the horizontal and vertical flow at small scales should improve our understanding on the gateways of exchange of heat, freshwater, carbon, and nutrients across the oceans, and between the surface and deeper layers, with a big impact on biogeochemical cycles and biomass evolution.

Surface Water and Ocean Topography will be in a non-sun-synchronous orbit, specifically designed to provide our best 2D observation of the coastal and high-latitude tides, and the ocean's internal tide field. This is a one-off opportunity – other planned wide swath missions for 2030+ are all on a sun-synchronous orbit, and will not resolve the full range of tidal constituents available with SWOT. This means that the SWOT era from 2022 to 2025 will be an exciting and unique opportunity to explore the role of internal tides and internal waves interacting with the "balanced" ocean circulation, and modifying the eddy energy, evolution and mixing on a global scale. Disentangling the balanced and unbalanced signals in SSH remains a challenge though, if we want to use SWOT or other fine-resolution alongtrack altimetry data to calculate balanced surface currents.

Mapping the fine-scale SWOT SSH swath data onto regular 2D fields presents many challenges, which are being explored using dynamical rather than statistical interpolation techniques, different vertical projection schemes, and full assimilation techniques. The improved small-scale sea surface height and surface currents from SWOT can also be analyzed in synergy with fine-scale satellite tracer data (SST, ocean color) and surface parameters (surface roughness, sun-glitter, etc.) that are strongly modified across fronts and filaments, in order to link the deeper dynamics with the surface fronts.

Finally, the altimetric mesoscale era was accompanied by a global Argo program that allowed us to collocate large-scale dynamics and eddies with vertical profiles. The question of how to collocate the rapidly evolving fine-scales observed by SWOT data with *in situ* data poses new challenges, that are actively being explored. Data mining of historical ADCP or glider data to re-analyze the high-frequency, fine-scales is one option. Developing new, rapid, fine-scale ocean profilers is another. Exploring the overlapping dynamics from small-scale ocean processes including internal waves and tides, using fine-resolution *in situ* and satellite data and models, will occupy a lot of our energy over the coming years.

AUTHOR CONTRIBUTIONS

All authors contributed to write sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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REVIEW
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From the Oceans to the Cloud: Opportunities and Challenges for Data, Models, Computation and Workflows

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Advances in ocean observations and models mean increasing flows of data. Integrating observations between disciplines over spatial scales from regional to global presents challenges. Running ocean models and managing the results is computationally demanding. The rise of cloud computing presents an opportunity to rethink traditional approaches. This includes developing shared data processing workflows utilizing common, adaptable software to handle data ingest and storage, and an associated framework to manage and execute downstream modeling. Working in the cloud presents challenges: migration of legacy technologies and processes, cloud-to-cloud interoperability, and the translation of legislative and bureaucratic requirements for "on-premises" systems to the cloud. To respond to the scientific and societal needs of a fit-for-purpose ocean observing system, and to maximize the benefits of more integrated observing, research on utilizing cloud infrastructures for sharing data and models is underway. Cloud platforms and the services/APIs they provide offer new ways for scientists to observe and predict the ocean's state. High-performance mass storage of observational data, coupled with on-demand computing to run model simulations in close proximity to the data, tools to manage workflows, and a framework to share and collaborate, enables a more flexible and adaptable observation and prediction computing architecture. Model outputs are stored in the cloud and researchers either download subsets for their interest/area or feed them into their own simulations without leaving the cloud. Expanded storage and computing capabilities make it easier to create, analyze, and distribute products derived from long-term datasets. In this paper, we provide an introduction to cloud computing, describe current uses of the cloud for management and analysis of observational data and model results, and describe workflows for running models and streaming observational data. We discuss topics that must be considered when moving to the cloud: costs, security, and organizational limitations on cloud use. Future uses of the cloud via computational sandboxes and the practicalities and considerations of using the cloud to archive data are explored. We also consider the ways in which the human elements of ocean observations are changing – the rise of a generation of researchers whose observations are likely to be made remotely rather than hands on – and how their expectations and needs drive research towards the cloud. In conclusion, visions of a future where cloud computing is ubiquitous are discussed.

Keywords: ocean observation, ocean modeling and prediction, cloud, data management, archiving, technology

DEFINING CLOUD COMPUTING AND PATTERNS FOR ITS USE

The most widely used definition of cloud computing is in Mell and Grance (2011):

> Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.
>
> Essential Characteristics:
>
> - On-demand self-service: A consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed.
> - Broad network access: Capabilities are available over the network and accessed through standard mechanisms that promote use by heterogeneous thin or thick client platforms.
> - Resource pooling: The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model.
> - Rapid elasticity: Capabilities can be elastically provisioned and released, in some cases automatically, to scale rapidly outward and inward commensurate with demand.
> - Measured service: Cloud systems automatically control and optimize resource use by leveraging a metering capability.
>
> Service Models:
>
> - Software as a Service (SaaS): The capability provided to the consumer is to use the provider's applications running on a cloud infrastructure.
> - Platform as a Service (PaaS): The capability provided to the consumer is to deploy onto the cloud infrastructure consumer-created or acquired applications created using programming languages, libraries, services, and tools supported by the provider.
> - Infrastructure as a Service (IaaS): The capability provided to the consumer is to provision processing, storage, networks, and other fundamental computing resources where the consumer is able to deploy and run arbitrary software (Mell and Grance, 2011).

For this paper, we define the cloud as shared, off-premises user configurable resources for data storage/discovery and computing.

Butler and Merati (2016) provide another view of the cloud. Following the framework of *A Pattern Language* (Alexander et al., 1977) and applications of patterns to object-oriented programming in Gamma et al. (1995), they define six patterns of cloud use:

Cloud-Based Scientific Data – Getting Data From the Cloud

Intent: Explores integrating the use of cloud-based data and how scientists can access large volumes of diverse, current and authoritative data, addresses the problem of locating and using large amounts of scientific data.

The Section "Architectures for Real-Time Data Management and Services for Observations" describes streaming data and an architecture for making it easy to gather data. Also see Johanson et al. (2016).

Cloud-Based Management of Scientific Data – Storing Data in the Cloud

Intent: Explores storing and managing data in the cloud. Addresses the problem of ever increasing data quantities with decreasing budgets for data management. Explores the ways scientific projects can meet data access and dissemination requirements such as the U.S. Public Access to Research Results (PARR) mandate (Holdren, 2013).

The section on the NOAA Big Data Project and open data and archiving are examples of this pattern. Also see Meisinger et al. (2009).

Computing Infrastructure for Scientific Research

Intent: Explores the ways in which cloud computing, in the form of PaaS or IaaS could be used as part of a research program and for teaching. It addresses the need for larger computational capabilities, especially under constrained budgets.

The modeling efforts described in later sections are examples of this pattern.

Analysis in the Cloud

Intent: Explores conducting analyses in the cloud. Addresses the problem of wanting to perform analyses on ever larger datasets and on datasets from multiple sources. Explores the secondary question of ways scientific projects can standardize analysis tools among geographically distributed researchers.

The section entitled "Architectures for Real-Time Data Management and Services for Observations" is an example of this pattern, as are Henderson (2018) and Gorelick et al. (2017).

Visualization

Intent: Explores creating visualizations using cloud-based tools and making the visualizations available via the cloud. Addresses the need to visualize larger amounts of data and the opportunities provided by improved graphics processors and display devices such as VR headsets.

The section entitled "Workflow on the cloud" shows examples of this pattern as does Allam et al. (2018). Workflow tools can visualize more than just the data, they can reveal unexpected dependencies, bottlenecks, and participants' roles.

Results Dissemination in Real Time/Storytelling/Outreach

Intent: Explores ways in which cloud-based platforms and tools can be used to reach new audiences. Addresses the need to make research results rapidly available and relevant to a wide variety of audiences – scientific and non-scientific (Butler and Merati, 2016).

The US Integrated Ocean Observing System (IOOS) Regional Associations' work described below are examples of this pattern.

CURRENT USES – OBSERVATIONS AND MODELS IN THE CLOUD

To expand upon the patterns above, three specific use cases are presented – one focused on using the cloud to disseminate data, a second one describing how the IOOS Regional Associations use a number of patterns for their observational and model data, and a third one based on the European Copernicus Marine Environment Monitoring Service and the capabilities of Google Earth Engine and Google Cloud Datalab. These use cases are intended to provide a pragmatic introduction to using the cloud and specific implementations, to describe what data or outputs and analysis/modeling tools have been moved to the cloud, to show preliminary results and challenges, and to tell where we see these projects going.

Observational Data in the Cloud: The NOAA Big Data Project

The U.S. National Oceanic and Atmospheric Administration's (NOAA) Big Data Project (BDP), announced in 2015, is a collaborative research effort to improve the discoverability, accessibility, and usability of NOAA's data resources. NOAA signed five identical Cooperative Research and Development Agreements (CRADAs) with collaborators: Amazon Web Services (AWS), Google Cloud Platform (GCP), IBM, Microsoft Azure, and the Open Commons Consortium (OCC). The BDP is an experiment to determine to what extent the inherent value in NOAA's weather, ocean, climate, fisheries, ecosystem, and other environmental data can underwrite and offset the costs of commercial cloud storage for access to those data. The project also investigates the extent to which the availability of NOAA's data on collaborators' cloud platforms drives new business opportunities and innovation for U.S. industry.

The BDP facilitates cloud-based access to NOAA data to enhance usability by researchers, academia, private industry, and the public at no net cost to the American taxpayer. One example is the transfer of NOAA's Next Generation Weather Radar (NEXRAD) archive to cloud object stores. The entire NEXRAD 88D archive (∼300 TB, 20 M files) was copied from NOAA's National Centers for Environmental Information (NCEI) to AWS, Google and OCC in October 2015. Marine datasets include elements of the NOAA Operational Forecast System (OFS[1]), sea surface temperature datasets, NCEP/NCAR reanalysis data, and some National Marine Fisheries Service (NMFS) Trawl, Observer, and Essential Fish Habitat data. The full list of available datasets can be found at https://ncics.org/data/noaa-big-data-project/. Under the CRADA, collaborators are allowed to charge for the "marginal cost of distribution." To date, however, none of the collaborators has implemented this provision.

Following the NEXRAD release on AWS:

- In March 2016, users accessed 94 TB from NCEI and AWS combined, more than doubling the previous monthly maximum from NCEI.
- The amount of outgoing NEXRAD Level II data from NCEI has decreased by 50%.
- New analytical uses of the NEXRAD data became manifest – bird migration, mayfly studies.
- 80% of NOAA NEXRAD data orders are now served by AWS.

(Ansari et al., 2017)

Another approach has been the integration of NOAA data into cloud-based analytical tools, including GCP's hosting of NOAA's historical climate data from the Global Historical Climatology Network (GHCN). By offering access through Google BigQuery, from January 2017 to April 2017 1.2 PBs of climate data was accessed via an estimated 800,000 individual accesses. This occurred without Google or NOAA advertising the availability of the data.

Thus far, the NOAA Big Data Project and the CRADA partners have published ∼40 NOAA datasets to the cloud. This has led to increased access levels for NOAA open data, higher levels of service to the data consumer, new analytical uses for open data, and the reduction of loads on NOAA systems. Some lessons learned to date include:

- There is demonstrable unmet demand for NOAA data – as additional services are made available, more total data usage is observed.
- Of equal value to NOAA's data is NOAA's scientific and analytical expertise associated with the data. By working with the CRADA partners to describe and reformat datasets, NOAA's expertise ensures that the "best" version

[1] https://docs.opendata.aws/noaa-ofs-pds/readme.html

of a data type or dataset is made available. If scientific questions arise, NOAA scientists can assist knowing exactly which version of the data is being used.

- Providing copies of NOAA's open data to collaborators' platforms to enable cloud-based access is a technically feasible and practical endeavor and it improves NOAA's security posture by reducing the number of users traversing NOAA networks to access data.
- Beyond the free hosting by cloud providers of several high-value NOAA datasets, another outcome of the NOAA BDP has been the development of an independent data broker entity or service that can facilitate publishing NOAA data on multiple commercial cloud platforms (**Figure 1**). The role of an intermediate "data broker" has emerged as a valuable function that enables the coordinated publishing of NOAA data from federal systems to collaborators' platforms, and could become a common Service supporting all of NOAA publishing data to the cloud.
- Integrating NOAA data into cloud-based tools, as opposed to simply making the original NOAA data files available, has great potential to increase usage. However, expertise and labor is required to properly load NOAA data into those tools.
- A defined commitment and level of service has emerged as a need for both NOAA and the collaborators for the partnership to be sustained.
- Noteworthy is the challenge in generating equal interest on the part of CRADA partners across all of the NOAA data domains. To date, weather related data has been the most requested as part of the NOAA BDP.

The NOAA Big Data Project is scheduled to end in May 2019. Looking toward the future, the BDP seeks, in discussions with current CRADA participants and NOAA managers, to define a sustainable partnership to continue providing cloud-based data access.

Cloud Use Within IOOS for Observational Data and Model Output

The Present

Within the Integrated Ocean Observing System (IOOS) enterprise, many Regional Associations (RA)[2] have migrated ocean observation data management and distribution services to the cloud. Cloud usage varies significantly between IOOS RAs, with some deploying most of their web service infrastructure on the cloud, some deploying infrastructure to shared data centers with or without cloud components, and others utilizing primarily on-premises infrastructure that sometimes includes a cloud backup capability.

IOOS Regional Associations' that have migrated some infrastructure to the cloud have focused on porting existing applications from their own infrastructure, and may not have re-architected to leverage the unique capabilities of cloud services. This represents an incremental approach to cloud adoption, as existing services and data on RA-owned hardware are migrated first, and then, as institutional familiarity with the cloud services grows, new features may be plugged in for better operation.

The most common use of cloud computing within IOOS' 11 RAs is for web applications and data access services. This includes data servers that provide both observation and forecast data to end users [e.g., THREDDS (Thematic Real-time Environmental Distributed Data Services), ERDDAP (Environmental Research Division's Data Access Program), and GeoServer], map-based applications, as well as standard web pages. IOOS RAs have

[2] https://ioos.us/regions

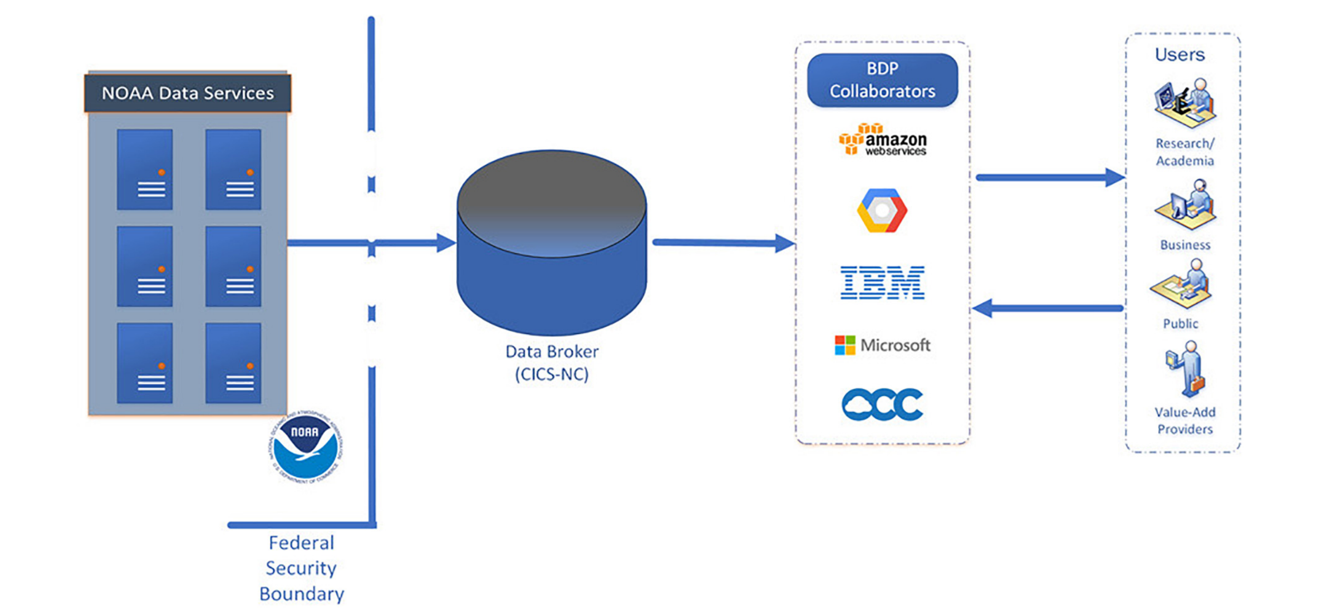

FIGURE 1 | Data broker architecture diagram for Cloud ingest (source: NOAA BDP). CICS-NC: Cooperative Institute for Climate and Satellites – North Carolina.

deployed THREDDS and ERDDAP servers on the cloud using both virtual machine and Docker runtime environments. The IOOS Environmental Data Server, or EDS[3], a web-mapping platform for oceanographic model visualization, is run on the cloud using the Docker platform. GLOS, the Great Lakes IOOS regional association, uses cloud-based virtual machines to run their buoy portal application and the Great Lakes acoustic telemetry system[4,5]. **Figure 2** depicts the number of RAs currently using, or planning to use within 2 years, the cloud for a particular use case.

Several RAs currently use or are actively investigating the cloud as a direct data ingest and storage service for near-real time observations. In this scenario, a server or service is deployed to a cloud-based resource as a direct ingest point for data telemetered from buoys or other sensors operated by the RAs or their affiliates. An example of this is GCOOS, the IOOS region for the Gulf of Mexico, and its affiliate Mote Marine Laboratory's use of a cloud-based instance of Teledyne Webb Research's Dockserver application. Dockserver receives data transmitted by a glider through the Iridium communications network and transfers it to the Internet. Mote's Dockserver has been cloud-based since 2010, receiving data packets in real-time from operational gliders via satellite downlink. Leveraging the cloud has provided a more stable operating environment for Mote's glider operations, and it is far less vulnerable to weather-related hazards than on-premises systems, especially if they are located on or near the coast.

[3]https://eds.ioos.us
[4]https://glbuoys.glos.us
[5]https://glatos.glos.us

GLOS is experimenting with transitioning their locally hosted near real-time data ingest system to a cloud-ready architecture. The primary change involves migrating from a custom sensor data ingest platform to one more suitable to leverage solutions such as AWS' Internet of Things (IoT) services. Currently, GLOS collects transmissions from deployed sensors in eXtensible Markup Language (XML) format via cellular modem to a locally managed secure file transfer protocol (SFTP) service, which then unpacks, stores, and distributes the data. In the new system, nearshore LoRaWAN (Long Range Wide Area Network) devices that connect to Internet-connected gateways may be used to transmit data using HTTP POST or MQTT (message queuing telemetry transport) to remote web services to read, store and re-publish the data. These web services could be more readily deployed on cloud platforms, or, if compatible, use the aforementioned IoT services provided by cloud vendors. GLOS will continue to investigate these pathways over the next 2 years along with its full-scale data center migration to the cloud.

The most significant value that cloud has provided to IOOS RAs to date is its reliability. CARICOOS, the IOOS region for the Caribbean, migrated much of their web presence and associated data services to AWS in 2015. The motivation for the move was mitigation of power grid reliability issues at their University of Puerto Rico's Mayaguez facility. Generator power proved insufficient, and the result was unreliable Internet, data flow, modeling, webpage, and THREDDS server uptimes.

CARICOOS experienced a significant reduction in outages after the migration. During the 2017 hurricane season, they were able to provide near continuous uptime for their most essential data flows, data services, and web pages for use in planning and executing relief efforts. Despite widespread power

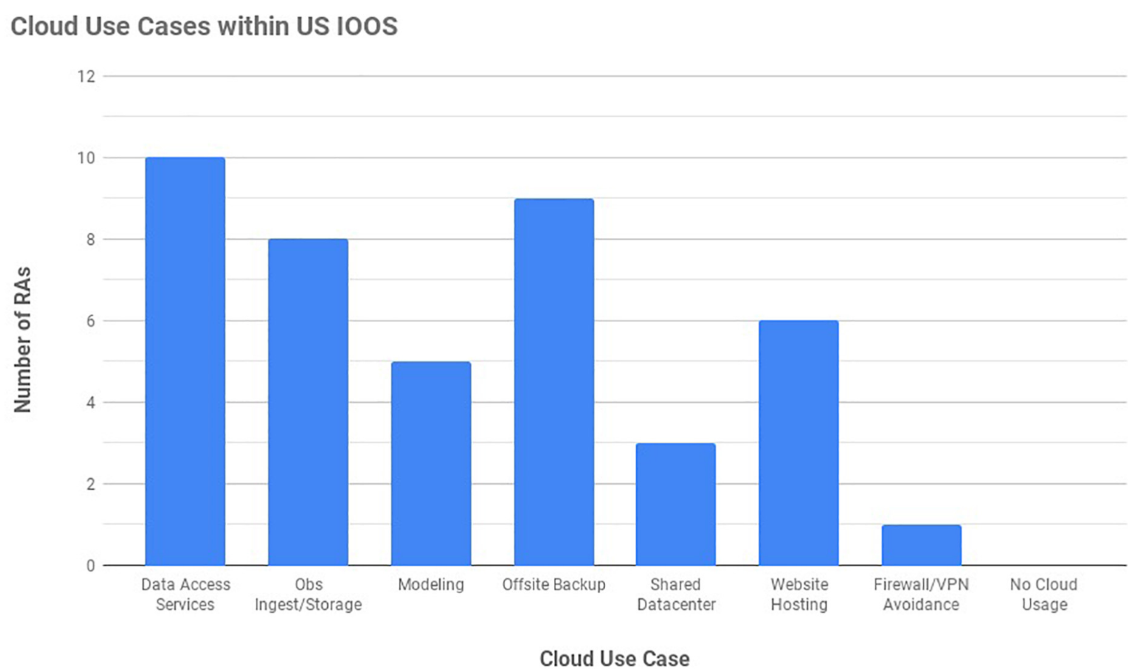

FIGURE 2 | Current and planned Cloud use within the IOOS Regional Associations.

outages and catastrophic damages sustained by Puerto Rico and other Caribbean islands during the hurricanes, CARICOOS' data buoys that had not been damaged in the storms were able to remain online.

Backup and redundancy are also common use cases for cloud computing. Since recovering from Hurricane Maria, CARICOOS has renewed their efforts to develop and test high-performance computing (HPC) ocean models in the cloud. CARICOOS' modelers have been experimenting with a regional high-resolution Finite Volume Community Ocean Model (FVCOM) on AWS, and next in line for migration are their Weather Research Forecast (WRF) implementations, Simulating Waves Nearshore (SWAN) and SWAN beach forecasts and an updated Regional Ocean Modeling System (ROMS). These models currently run on local servers and CARICOOS' goal is to maintain local-cloud redundancy in their operational modeling efforts.

Several of IOOS' RAs have organizational characteristics that affect decisions on whether or not to embrace the cloud. Several RAs share a common IT provider, which pools resources and runs its own self-managed data center similar to a cloud service. This data center is housed in a co-location facility and provides an expandable pool of compute nodes and other resources that allow the RAs to meet customer needs for data services. While no true cloud backup exists yet for this system, it is architected to allow a future cloud migration either in the case of emergency or if it makes economic sense to do so. Many IOOS RAs are affiliated with public universities or other research organizations that provide lower cost internal IT support and services, including data management and web publishing infrastructure. Due to these affiliations, the RAs can take advantage of considerable organizational investment in IT infrastructure and support that would have to be replicated in a cloud environment. In effect, this makes the decision to adopt the cloud an indirect one for these RAs: if their parent organizations or IT provider decide to make the move, they will be included.

The RA for the Pacific Islands, PacIOOS (Pacific Islands Ocean Observing System) is run primarily through the University of Hawaii (UH). The University provides IT infrastructure in the form of server rooms, cooling, network connectivity and firewalls at minimal costs (charged as an indirect cost to the grant). Thus, for an initial investment in hardware, PacIOOS established a variety of IOOS recommended data services, and obtained relatively secure data warehousing for individual observing system components – gliders, High Frequency Radars, model output, etc.

Two of PacIOOS' higher use datasets include real-time observations supplied by offshore wave buoys and forecasts from numerical models. PacIOOS THREDDS servers distribute hundreds of gigabytes of data per month of these data, risking large data egress costs on commercial cloud platforms and making the cloud not yet economically viable. Bandwidth and latency for data publishing is also a concern. PacIOOS forecast models generate about 15 GB/day in output. These models are run on UH hardware, and it is no problem getting the data between modeling clusters and the PacIOOS data servers, whereas bandwidth limitations might affect routine data publishing workflows to the cloud. High volume modeling input/output (I/O) can be handled efficiently on local hardware.

The Future

Challenges, cost barriers, and inertia aside, commercial cloud platforms increasingly offer novel services and capabilities that are difficult or impossible to replicate in an on-premises IT environment. Managed services, aka "software-as-a-service," provide flexibility and scalability in response to changes in user traffic or other metrics that are not easily replicated in self-owned systems and environments. "Serverless" computing, where predefined processes or algorithms are executed in response to specific events, offers a new way to manage data workflows, and are often priced extremely competitively when their unlimited elasticity and zero-cost for periods of non-operation are factored in. Event-based computing using serverless cloud systems is well suited to real-time observation processing workflows, which are inherently event-driven.

For IOOS, or other observing systems, the cloud may become compelling as these features are improved and expanded upon. Instead of data first being telemetered to a data provider's or RA's on-premises servers, it could be ingested by a cloud-based messaging platform, processed by a serverless computing process, and stored in a cloud-based data store for dissemination, all in a robust, fault- and environmental hazard-tolerant environment.

In summary, the motivations and benefits in adopting cloud-hosted services for IOOS RAs have so far been the following:

- Locally available computing infrastructure and/or power grids can be unreliable.
- The operational cost of cloud hosting can be lower. The cost of cloud hosting is highly dependent on a particular application, but IOOS could develop a set of best-practices to end up with lower costs for cloud hosting.
- Hardware lifecycle costs are reduced. The periodic replacement of critical server and network infrastructure is eliminated with cloud-hosted services.
- Cloud scalability can help meet user data request peaks.
- Greater opportunity for standardization exist by providing all RAs with a standard image for commonly used data services.

Undertaking a cloud migration is not without challenges, however. Data integrity on cloud systems must be ensured and characterized accordingly in data provenance metadata (see Section "Data integrity: How to Ensure Data Moved to Cloud Are Correct"). Users must have confidence in the authenticity and accuracy of data served by IOOS RAs on cloud providers' systems, and the metadata provided alongside the data must be sufficiently developed to allow this. The IOOS RA community will need to balance these and other concerns with the potential benefits both in choosing to move to the cloud and in devising approaches by which to do so.

Copernicus and Google: Earth Engine, Cloud and Datalab

Copernicus is the European Union's Earth Observation Program. It offers free and open information based on satellite and *in situ* data, covering land, ocean and atmospheric observations, (European Space Agency, 2019a). Copernicus is made of three components: Space, *in situ*, and Services. The first component, "Space," includes the European Space Agency's (ESA) Sentinels, as well as other contributing missions operated by national and international organizations.

The second component of Copernicus, "*in situ*," collects information from different monitoring networks around Europe, such as weather stations, ocean buoys, or maps. This information can be accessed through the Copernicus Marine Environment Monitoring Service (CMEMS) (European Space Agency, 2019b). CMEMS was established in 2015 to provide a catalog of services that improved knowledge in four core areas for the marine sector: Maritime Safety, Coastal and Marine Environment, Marine Resources, and Weather, Seasonal Forecasting, and Climate. The *in situ* data is key to calibrate and validate satellite observations, and is particularly relevant for the extraction of advanced information from the oceans.

Sentinel data can be accessed through the dedicated Copernicus Open Access Hub (European Space Agency, 2019c), and can be processed using the Sentinel-2 and Sentinel-3 Toolboxes (Copernicus, 2019a,b), but Google Earth Engine (GEE) and Google Cloud (GC) provide a simplified environment to access and operate data online (Google Cloud, 2019; Google Earth Engine, 2019). The data is accessible through GC Storage and directly available using the GEE dedicated platform. The access and management of GEE is simplified using a Python API which interacts with the GEE servers through the GC Datalab (Google Cloud Datalab, 2019). The Datalab allows advanced data analysis and visualization using a virtual machine within the Google datacenters, allowing high processing speeds by means of open source coding. Moreover, the Datalab is also useful for machine learning modeling, which makes it very interesting when working with different marine *in situ* and satellite data combinations.

The main limitation of these set of tools is the lack of integration between some data sources and the virtual environment. At the moment, satellite data is stored in the cloud, but *in situ* data is just available through the dedicated Copernicus service, making the process of downloading and accessing this information not as straightforward as in the Earth observation case. However, the inclusion of machine learning techniques and a dedicated language for satellite data treatment makes the use of GEE very attractive, especially for academic and R&D applications. The Google computing capabilities make the GEE-GC-Copernicus combination a realistic option for future ocean observation applications.

OPERATIONAL CONSIDERATIONS

Costs

Comparing the cost of working in the cloud with traditional local computing is a challenge. Deciding which costs should be included to make an equitable comparison requires considering factors such as true infrastructure costs – not only the purchase of hardware but the costs of housing it, utility costs, the cost of personnel to run the system, and how long it will be before the system needs to be replaced. Systems hosted at universities may have unusually low costs due to State or other support – should these costs be used or should the true cost be calculated without external support? On the other hand, cloud providers may provide reduced cost resources or grants of compute time and storage to help new users move to the cloud. The terms and conditions of these grants may affect the long term costs of migrating and may also introduce concerns about data ownership.

Differences in use also affect estimating costs. A project that only involves storing data in the cloud is easy to price out, and the costs of the various types of storage can be balanced against the rapidity with which the data are needed. The benefits of compressing data and finding ways to reduce the size and frequency of data egress from cloud storage can be fairly easily determined. Maintenance of data in the cloud should also be included in cost estimations. The cost of running a model in the cloud is much harder to compute due to variables such as number of virtual machines, the number of cores, what compilers or libraries are needed, grid sizes and time steps, what output files need to be downloaded, and whether analyses of the output can be done in the cloud. If the model is to be used for real time forecasting, then the wall clock run time of the model is critical and may require more expensive compute options to ensure that runs are completed in time.

Molthan et al. (2015) described efforts to deploy the Weather Research and Forecast (WRF) model in private NASA and public cloud environments and concluded that using the cloud, especially in developing nations, was possible. Cost ran from $40–$75 for a 48-h simulation over the Gulf of Mexico.

Mendelssohn and Simons (2016) provide a cautionary tale on deploying to the cloud. As a part of the GeoCloud Sandbox, they deployed the ERDDAP web-based data service to the cloud and concluded that hosting the service in-house was still cheaper. They also found that, except in cases of one-time or infrequent needs for large scale computation, the limitations described in Section "Limitations/Barriers Imposed by U.S. Government Policies" could easily make use of the cloud untenable.

Siuta et al. (2016) looked at the cost of deploying WRF under updated cloud architectures and options and described how resource optimization could reduce costs to be equivalent to on-premises resources.

Generally, running in the cloud can be equal to, or possibly cheaper than running on-premises, but reaping the full benefits requires tuning and experimentation to get the best performance at the lowest cost.

Security

Security concerns are often cited as an impediment to cloud adoption, especially by government researchers. Adoption requires a shift in thinking on the part of institutional security managers from how to secure their resources, via mechanisms such as firewalls and trusted connections, and a shift on the part of users from hardware that they can see and manage to the more amorphous concept of unseen virtual machines. Unless on-premises infrastructures for data services are completely isolated from public networks, the logical access requirements for on-premises and cloud-hosted infrastructure are very similar. Physical access to local infrastructure is visible, while physical access to cloud hosting solutions is less easily observed. Commercial cloud providers go to great effort to ensure the security of their data centers and users should ensure that these meet local IT requirements.

While the challenges are real, arguably the cloud can be the safest place to operate. Cloud operating systems are up to date on patches and upgrades, redundancy in disks ensures rapid recovery from hardware failures, tools such as Docker can containerize an entire environment and allow for rapid restarts in case of problems, and the fact that cloud systems need to meet commercial level security/data confidentiality requirements drives additional levels of system resilience. Coppolino et al. (2017) provide a good review of cloud security. While their paper is aimed more at business needs, their observations and conclusions are equally valid for scientific data. NIST also provides guidelines on security and privacy in the cloud (Jansen and Grance, 2011; Joint Task Force, 2017).

Limitations/Barriers Imposed by U.S. Government Policies

The dichotomy in U.S. Federal Government IT positions when policy is compared to strategy is evident with regards to cloud services. The U.S. Government proclaims an affinity for cloud services and has done so for the last 8 years (Kundra, 2011; American Technology Council, 2017). The biggest hurdle to cloud adoption has not been technical implementation, nor a lack of desire; it has been Federal IT policy. Offices using cloud services have had to deal with extensive re-engineering and documentation efforts to retroactively address IT requirements. While the merits of Federal IT policy are not under evaluation, it does not lend itself to rapid adoption for cloud services.

Here are notable policy barriers to Federal cloud adoption:

1. All cloud services used by the Federal Government must be FedRAMP approved. The Federal Risk and Authorization Management Program, FedRAMP, is a program established to ensure IT services are secure. While major cloud platform providers have undertaken the cost to ensure their FedRAMP certification, most smaller providers are not incentivized to spend the resources on FedRAMP approval.
2. All Federal IT traffic has to be routed via a Federally approved Trusted Internet Connection (TIC). This policy requirement is particularly onerous and restrictive to cloud adoption. It requires cloud users to configure or purchase dedicated secure routing between the cloud host provider and the end user. This places a large configuration burden and cost upon users, and might force the use of lower performing virtual private network (VPN) solutions. This requirement also negates the opportunity to leverage IT infrastructure co-location benefits with non-Federal collaborators due to the additional network latency added by the Federally derived network traffic routing. Plans are being developed to address the burdens of the TIC requirement (Federal CIO Council, 2018).
3. Federal cloud deployments are not exempt from any of the IT configuration/security requirements that apply to on-premises deployments. For example, the requirement for various monitoring and patch control clients to be installed on Federal IT systems is a hurdle as these clients are not available for many cloud platforms.
4. Procurement, especially the prescriptive nature of the Federal Acquisition Regulation (FAR) does not lend itself well to cloud adoption. Cloud providers innovate rapidly and, when developing contract requirements, it is impossible to know what future services may be available for a particular business need; thus handicapping some of the innovation potential of cloud solutions. Plans have been released for the US Government to develop cloud service catalogs to increase the efficiency with which the government can procure cloud services[6].
5. Budgeting, specifically in relation to cloud procurement, can be challenging. One of the primary advantages of cloud computing is the flexibility to scale resources based on demand. Budgeting in advance is therefore difficult or impossible: allocate too little and risk violating the Anti-Deficiency Act; allocate too much and risk needing to de-obligate unused funding at the end of the contract. NASA, as part of the Cumulus project on AWS, has developed monitoring functions for data egress charges (Pilone, 2018). In practice, they effectively operate without restriction until the budget limit is reached, and then shut down. This is not an optimal solution if users depend on continuous data availability.

These factors diminish the benefits of nimble deployment and increase the cost and complexity of Federal cloud applications.

Data Integrity

Data integrity addresses the component of data quality related to accuracy and consistency of a measurement. It is extremely important to ensure the quality of data that are used in the assessment of our environment. Broad confidence in the integrity of data is critical to research, and decisions driven by this research. The preservation of data integrity is an important consideration in the complete data lifecycle.

Software considerations for cloud hosted data processing and data management processes are no different from those hosted on-premises. Software should be tested and versioned, and the version of software used in the manipulation of the data should be cataloged in metadata. While most of the software on a cloud-hosted solution are bespoke solutions written for specific data needs, a component in a software architecture can depend on cloud host provided infrastructure. Often these solutions are unique to a particular cloud provider. Examples are the stores provided by popular commercial cloud platforms. Unlike commonly used open-source relational database servers or other storage frameworks, the inner working of these data stores are proprietary, and therefore opaque to the data manager. This raises the concern of the potential for data errors that could be

[6] https://cloud.cio.gov/strategy/

introduced and affect the integrity of hosted data. It is imperative that methods, such as periodic checksum verification, be applied to ensure data integrity are preserved over the lifetime of the cloud-hosted storage.

Due to the off-site nature of cloud hosting, serious consideration should be given to the preservation of data integrity during the data transmission from on-premises facilities to cloud hosting. The financial sector has placed a heavy emphasis on this subject and the environmental data sector can benefit greatly from tapping into methodologies and processes developed by other sectors. One such technology is Blockchain.

Blockchain, or digital general ledger technology, is a category of technologies that record transactions between two parties as digital encrypted records, or blocks. As each block contains a digital reference to the previous record as a cryptographic hash, these records create an immutable chain of transactions, or a blockchain. Blockchain implementations are often distributed, and by design can track transactions on many different computers. Many commercial Blockchain solutions are available, and this technology is widely used, especially in the financial sector. The transactions embedded in a blockchain, combined with the immutability of embedded metadata, makes this technology a favorable framework for data provenance tracking. In combination with digital checksums computed against the data embedded in the Blockchain entries, this technology can also support elements used to ensure data integrity. The decentralized nature of Blockchain makes it ideally implementable on cloud solutions and distributed data management systems. Blockchain is a complex topic, worthy of a discussion by itself. For an introduction to using blockchain in science, see Brock (2018) and Extance (2017).

These important considerations that could affect the short and long term integrity of the data are critical to maintain trust in data, but do not detract from the benefits of cloud hosted data processing and data storage.

EMERGING CLOUD TECHNOLOGIES FOR OBSERVATIONS AND MODELING

Architectures for Real-Time Data Management and Services for Observations

Rapidly growing volumes of application-, user-, or sensor-generated data, have led to new software tools built to process, store, and use these data. Whether the data are primary, as in the case of sensor-generated data streams, or ancillary, such as application-generated log files, software stacks have emerged to allow humans to understand and interpret these data interactively and downstream applications to monitor them continuously for abnormal behavior, change detection, or other signals of interest.

While observation data do not always constitute "big data," sensor data in general fits this classification, especially as the measurement frequency of the sensor increases. Low measurement frequency may be due to limitations in communication standards or speeds (i.e., satellite communications costs and the opacity of the ocean to radio frequencies) or in the data processing pipeline that prevent more frequent measurements, not limitations of the sensors themselves. Real-time data streaming applications have the potential to change this paradigm. Combined with server-based Edge computing and the scalability of cloud platforms as execution environments, there is the potential to measure ocean conditions on scales and at precisions not previously possible.

Cloud platforms also reduce the geographic risk associated with research-grade ocean observation systems. Typically, an institution deploys sensors into the ocean and communicates and/or downloads data from them via a "base station" – a physical computer at said institution. In extreme weather events – situations where ocean observing data are critical to decision-making – the stability of the physical computer can be compromised due to power outages, network connectivity and other weather-related nuisances. Putting the software required to keep observing systems running into a cloud system can mitigate most of the geographic risk and provide a more stable access point during events.

One processing model that adapts well to the cloud is stream processing, a technology concept centered on being able to react to incoming data quickly, as opposed to analyzing the data in batches. It can be simplified into three basic steps:

- Placing data onto a message broker
- Analyzing the data coming through the broker
- Saving the results

Stream processing is a natural fit for managing observational ocean data since the data are essentially a continuous time-series of sensor measurements. Data from ocean sensors, once telemetered to an access point, can be pushed to a data-streaming platform (such as Apache Kafka) for analysis and transformation to a persistent data store. Many streaming platforms are designed to handle large quantities of streaming data and can scale up by adding additional "nodes" to the broker as data volume increases. As data volume increases, the analysis may also need to increase. This can be done by increasing the resources available to the analysis code or by adding additional analysis nodes. Each streaming platform is different and has its advantages and disadvantages that should be taken into account before deciding on a solution. Vendor provided end-to-end systems include GCP Dataflow, AWS Kinesis, and Azure Stream Analytics.

An example cloud-architected system for ocean observation data handling system could use this workflow:

> Stream system is spun up on cloud resources and, using the provided client tools, is hooked into receive a continuous stream of ocean observations from multiple stations.

Processing code is written using the provided client application programming interfaces (APIs) to:

1. Quality control the data – detect missing/erroneous data using Quality Assurance of Real Time Oceanographic Data (QARTOD) and other quality control software.

2. Alert managers and users based on pre-defined or dynamic conditions.
3. Calculate running daily, weekly and monthly means for each parameter.
4. Store processing results back onto the processing stream as well as in a vendor-supplied analytical-friendly data format, such as AWS Redshift or BigTable, for additional analysis.
5. Export data streams to Network Common Data Form (netCDF) files for archiving and hosting through access services.

The architectures described above provide a number of tools to better support data stewardship and management when setting up a new system and workflow in the cloud. Some of these needs and opportunities will be described in later sections on data provenance, data quality and archiving. Migrations of existing applications have taught helpful lessons in coherently answering the question "hey wait, who's responsible for these data?" as they move along the pipeline from signals to messages to readings in units to unique records to collated data products to transformed information. Migration will require reexamining data ownership – is it correctly documented, will moving to the cloud intentionally or unintentionally transfer ownership to another entity, and who will maintain the data in the cloud – and how useful the data are for further computations or analyses. The following section addresses some of these questions and challenges.

Modeling Workflows in the Cloud

The traditional workflow for ocean modeling is to run a simulation on an HPC cluster, download the output to a local computer, then analyze and visualize the output locally. As ocean models become higher resolution, however, they are producing increasingly massive amounts of data. For example, a recent one-year simulation of the world ocean at 1 km resolution produced 1PB of output. These data are becoming too large to be downloaded and analyzed locally.

The cloud represents a new way of operating, where large datasets can be stored, then analyzed and visualized all in the cloud in a scalable, data-proximate way. Data doesn't need to leave the cloud, and can be efficiently accessed by anyone, allowing reproducibility of results as well as supporting innovative new applications that efficiently access model data. Moving analysis and visualization to the cloud means that modelers and other researchers need only lightweight hardware and software. The traditional high-end workstation can be replaced by a simple laptop with a web browser and cell-phone-hotspot-level Internet connection.

With these benefits come new challenges, however, some cultural, some technical and some institutional. We will examine the benefits of the Cloud for each component of the simulation workflow and then discuss the challenges.

Simulation and Connectivity Between Nodes

Numerical models solve the equations of motion on large 3D grids over time, producing 4D (time, depth, latitude, longitude) output. To reduce the time required to produce the simulation, the horizontal domain is decomposed into a number of small tiles, with each tile handled by a different CPU in a parallel processing system. Because the information from each tile needs to be passed to neighboring tiles, interprocess communications require high throughput and low latency.

For large grids that require many compute nodes, this traditionally has meant using technologies such as Infiniband. Of the major cloud providers, Microsoft Azure offers Infiniband (200 Gb/s), Amazon offers an Enhanced Network Adaptor (20 Gb/s) and Google offers no enhanced networking capability. Because cloud providers provide nodes with sizes up to 64 cores, however, smaller simulations can be run efficiently without traversing nodes. In many cases, simulations with hundreds of cores perform reasonably well on non-specialized cloud clusters, depending on how the simulation is configured.

Storage

Model results are traditionally stored in binary formats designed for multidimensional data, such as NetCDF and hierarchical data format (HDF). These formats allow users to easily extract just the data they need from the dataset. They also allow providers the ability to chunk and compress the data to optimize usage and storage space required.

While these formats work well on traditional file systems, they have challenges with object storage used by the Cloud (e.g., S3). While NetCDF and HDF files can simply be placed in object storage and then accessed as a filesystem by systems like FUSE, the access speed is very poor, as multiple slow requests for metadata are required for each data chunk access. This has given rise to new ways to represent data that use the NetCDF and HDF data models on the Cloud. The Zarr format, for example, makes access to multidimensional data efficient by splitting each chunk into a separate object in cloud storage, and then representing the metadata by a simple JSON (JavaScript Object Notation) file.

With cloud storage, there are no limitations on dataset size, and the data is automatically replicated in different locations, protecting against data loss. A large benefit of storage data on the Cloud is that the buckets are accessible via HTTP (HyperText Transfer Protocol), so efficient access to the data is possible without the need for web services like THREDDS or OPeNDAP (Open-source Project for a Network Data Access Protocol).

Analysis

Analysis of model data on the Cloud is greatly enhanced by frameworks that allow parallel processing of the data (e.g., Spark, Dask)[7]. This takes advantage of the Cloud's ability to allow arbitrary scale up processing. An analysis that takes 100 min on one processor costs the same as an analysis that takes 1 min on 100 processors. The analysis runs on the Cloud, near the data, and with server/client environments like Jupyter, the only data transferred are images and javascript objects to the user's

[7] http://docs.dask.org/en/latest/spark.html

browser. The Pangeo (2018) project is developing a flexible, open-source, cloud-agnostic framework for working with big data on the Cloud, using containers and container orchestration to scale the system for number of users and number of processors requested by each user.

Visualization

Display of data on large grids or meshes is challenging in the browser, but new technologies like Datashader allow data to be represented directly if the number of is polygons is small, but represented as dynamically created images if the number of polygons is large (**Figure 3**). Signell and Pothina (2019) used the Pangeo framework with these techniques to analyze and visualize coastal ocean model data on the Cloud.

Challenges

There are several challenges with moving to cloud simulation, storage, analysis and visualization of model data. Likely, the largest is the apparent cost. Computation can appear expensive because local computing is often subsidized by institutional overhead in the form of computer rooms, power, cooling, Internet charges and system administration. Storage is often expensive but offers increased reliability and the benefit of sharing your data with the community, essentially getting a data portal for free (Abernathey, 2018). The main challenge therefore might be getting institutions and providers to calculate the true cost/benefit of local vs. cloud computing and storage.

THE FUTURE IN THE CLOUD: OPPORTUNITIES AND CHALLENGES

Open Data Hosting

With continued growth in volume of both ocean observations and numerical ocean model output, the problem of how and where to efficiently store these data becomes paramount. As described earlier, the commercial cloud can accept massive volumes of data and store them efficiently in object storage systems, while also enabling new data analysis approaches (Pangeo, 2018). Setting aside costs, migrating open data to commercial cloud provider platforms offers clear technical advantages, but we must consider the potential pitfalls alongside the benefits.

If we take the assumption that all ocean data generated by IOOS, NOAA, or other publicly funded scientific organizations should be freely available and accessible for public use, as stewards of these data we must consider any downstream implications of where we store these data, including storing them on the cloud. Fair and equitable access to ocean data for users,

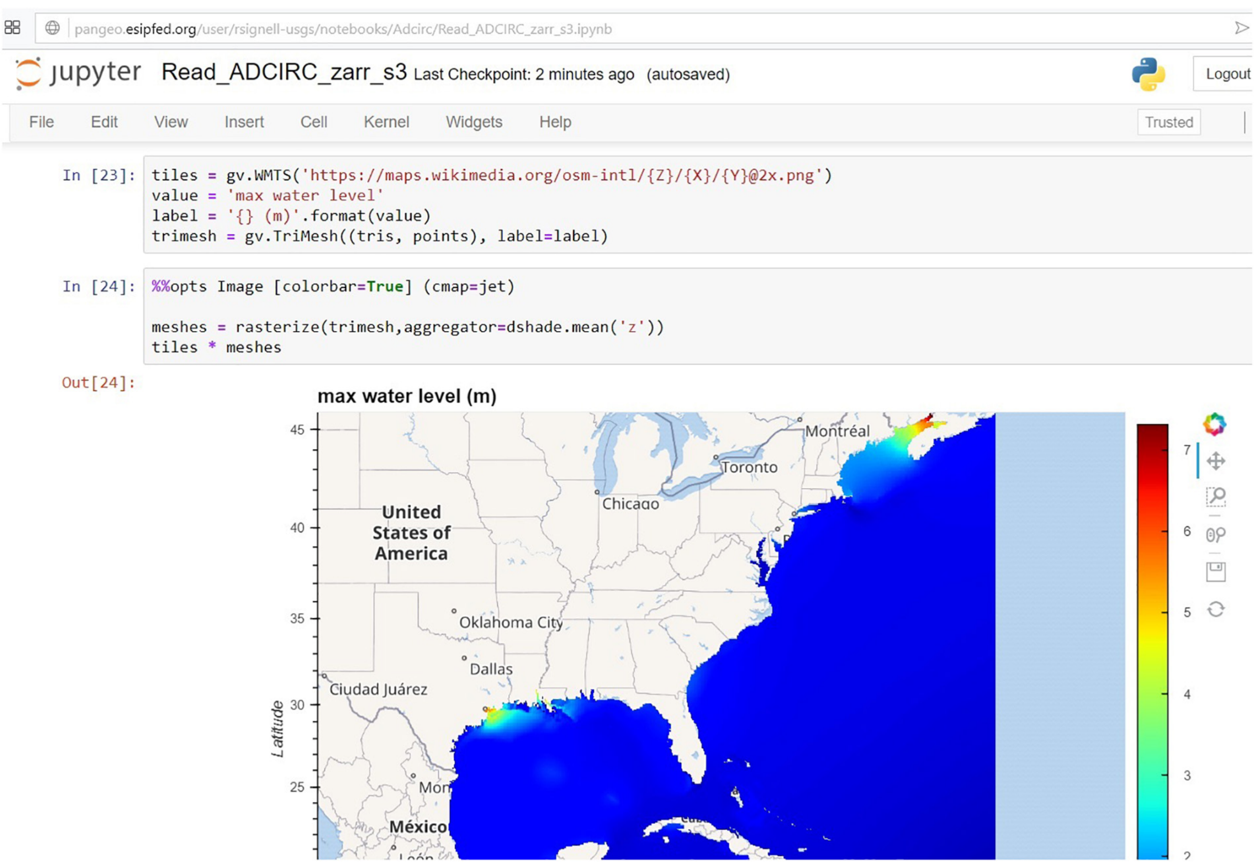

FIGURE 3 | Hurricane Ike simulation on a nine million-node mesh, displayed using Datashader in a Jupyter notebook.

assurance of long-term preservation, archival and continuous access, and flexibility for users to choose the environment in which they use the data, are all factors we must consider.

Already, some earth observing organizations (EOSDIS, 2018) are anticipating that the sheer growth in size of the data they collect will make it prohibitively expensive and complex to host within their own data centers. In this situation, commercial cloud storage services offer an effectively infinite ability to scale to meet their projected data storage needs. Similarly, we can expect ocean data holdings to someday eclipse our abilities to efficiently manage the systems to store them.

As a result, organizations may choose to migrate both the primary public copy of their data, as well as the standards-based services – such as OPeNDAP or Open Geospatial Consortium (OGC) Web Coverage Service (WCS) – users depend on for access, to the cloud. Discontinuing on-premises data hosting entirely can eliminate the need to maintain increasingly complex systems, relying instead on cloud vendors' almost infinite scalability. While this may seem a transparent change for end users, it may not be; there may be indirect implications of this choice on users of our data.

As highlighted earlier, open data that is available on a commercial cloud platform enables users to deploy massively parallel analyses against them. This is becoming known as the "data-proximate" computing paradigm (Ramamurthy, 2018; Pangeo, 2018). This is a breakthrough capability and one very likely to facilitate new discoveries from data that were either not previously possible, or not readily available at costs manageable for most users.

Data-proximate analyses such as these are most efficiently done only when the user provisions computing resources on cloud platform where the data resides. If we move our public, open data to a cloud provider, we may as a result be determining cloud platform suitability for end users looking to run these types of analyses, limiting them to only use the cloud host of our choice. If we move our open data exclusively to a single cloud provider, we lose a degree of impartiality as data brokers compared to when we self-host. We are in effect incentivizing users to come with the data to a particular provider.

Furthermore, the possibility is very real that if one ocean data provider organization selects Amazon, while another selects Google, and yet another selects Microsoft, it will be impossible for a single end user to run data-proximate analyses efficiently without first performing a data migration step to bring each source dataset to a common cloud platform for their compute workflows. If the data are massive, migration likely would not even be an option if the user does not have substantial resources to pay to self-host a copy of it. Fragmentation of data between competing clouds has the potential to negate, or at least lessen, the potential gains of "bringing the compute to the data" as the phrase goes.

These are both issues that deserve recognition and an effort to resolve as the earth observation community undertakes a migration to the cloud. As publishers and stewards of publicly funded open data, it is our responsibility to ensure fair and equitable access to the data for users (Project Open Data, 2018). Budgets, however, are limited, and because of the cost implications for storage and data egress from the cloud, we may not be willing or able to pay to replicate our data on multiple cloud platforms. If we were to try, what criteria would we use to determine which providers to use? Costs and performance would be typical selection factors for contract solicitations, but if, for our users' sake, we must factor in our decision which provider or providers other data publishers have used to host their data on, the picture gets complicated. As soon as data is moved from institution-owned systems, the calculus to determine "fair and equitable" changes.

So what can be done? Standard practice is for individual data provider organizations to sign contracts with commercial cloud providers to host their open data at prearranged costs to the organization. This accomplishes the individual organization's goal to migrate to the cloud, however, it does nothing to address either of the above issues. As an earth observation open data community as a whole, perhaps we can leverage the inherent value of our data to advocate for solutions that meet both our and our user communities' needs.

A technical solution to these issues might be to encourage cooperation among the cloud providers to replicate cloud-hosted public open data on their own. In exchange for signing a pay-for-hosting contract as described above, they could require the provider offer a free data replication service to their competitors, separate from standard data egress channels. Costs for such a service would be borne by the cloud providers, hence a strong push as a community might be necessary to spur its development. Downstream cloud providers would have to self-host open datasets they were not being paid to host in the first place, and each would have to make a cost/benefit decision whether to replicate the data or not, similar presumably to the decision made by participants in NOAA's BDP to host a particular dataset – it would need to have value to their business.

From a technical perspective, a service like this might resemble the following:

- The cloud provider hosting the data would provide a free, authenticated API endpoint that a well-known competitor cloud provider would be able to access to pull new data as it arrives. There would need to be a means to restrict access to this service to legitimate competitor cloud providers in order to prevent standard users downloading the data from circumventing egress charges due to be paid to the primary provider.
- A notification service would allow the downstream cloud provider to subscribe to receive update notifications of new or modified datasets, helping ensure data is kept in sync from one provider to the next.
- Finally, checksums for each data granule or "object" in a cloud data store would be generated and provided via the API to ensure integrity of the duplicated data, or a blockchain-based technology, as described in Section " Data integrity: How to Ensure Data Moved to Cloud Are Correct," might be deployed to accomplish this.
- Costs for the data replication service would either be paid by the original cloud provider hosting the organization's data, or passed back to the original data

publishing organization. In the case of the data publishing organization, this might need to be a part of the organization with archiving/stewardship responsibilities and accompanying funding/budget or a funding agency with similar requirements and responsibilities.

Stepping back from the technical, large organizations such as NOAA that publish many open datasets of high-value to users – including potential future customers for cloud providers – can leverage this value to negotiate free or reduced-cost hosting arrangements with the providers. NOAA's Big Data Project is an attempt to accomplish this. The "data broker" concept conceived by the NOAA BDP is a possible independent, cloud-agnostic solution to the one dataset-one cloud problem, making it easier for competing cloud providers to replicate to their own platforms agency open data published there.

It remains to be seen how much NOAA open data cloud providers are willing to host at no cost to the agency because of the BDP. If NOAA can negotiate free hosting of less commercially valuable data in exchange for technical expertise, including a data broker service, to assist in transfer of its more valuable data, then this lessens the cost of hosting data on multiple clouds and may be the best solution to avoid fragmenting NOAA's data among the clouds. For smaller data publishers, however, this negotiation is less likely to be feasible, and a single-cloud migration is the most likely option for them. In this case, a cloud-to-cloud data replication service might be the best path to ensure their data remains truly "open," and platform-neutral.

A final option for open data providers concerned about equitability is whether to eschew the cloud entirely, or to continue self-hosting data that they also move to the cloud. Either approach carries risks, either of technical obsolescence in the former, or excessive cost and technical complexity to manage two parallel data hosting systems in the latter – likely a deal-breaker for most budget-restricted data publishers.

Time may tell, as more public open data is moved from institution-owned systems to commercial cloud providers, whether cloud-by-cloud data fragmentation or the risk of inadvertently forcing users in co-locating computation on clouds alongside data are significant or not. The open data community as a whole, however, should plan a cloud migration carefully and considerately, and avoid the potential for adverse effects on our users.

Sandboxes in the Cloud for Modeling and Development

Adapting an on-premises high-performance computing environment used to execute ocean model simulations to a commercial cloud environment can be a challenging undertaking. Commercial cloud platforms, however, offer services not available in standard HPC environments that offer significant returns on investment for ocean modeling once the time and effort is taken to leverage them properly.

A computing sandbox is an isolated computing environment where researchers and others may test and develop new applications and workflows. In the computer security realm, they are a place where code and tools can be downloaded and examined without risking malicious damage to operational systems. In research, a sandbox can be a way for a funding source or other entity to provide computing resources to new users of the cloud so they can try-out migrating to the cloud. The sandbox is a communal resource and users are allowed to spin up new virtual machines with limited oversight. Cloud sandboxes support agile development and allow users to try out new ideas. The sandbox is usually a dynamic resource in that virtual machines are expected to be in use for short periods, may be taken down unexpectedly, and should not be used for operational applications. They are a place to "fail small."

One of the first cloud sandboxes for ocean research was the Federal Geospatial Data Consortium (FGDC) cloud sandbox, started in 2011[8]. This sandbox provided IaaS and PaaS and explored the logistics of managing a shared resource. Applications included particle tracking of larval fish, spatial data warehousing, and deployment of an ERDDAP installation.

From 2011 to 2014, the European Commission funded GEOSS interoperability for Weather, Ocean and Water (GEOWOW) project explored expanding the Global Earth Observation System of Systems (GEOSS) in general and the GEOSS Common Infrastructure (GCI). Deployment was on the Terradue Developer Cloud Sandbox and the results provided better access to datasets by centralizing their location and getting them out from behind firewalls and a sandbox for access to and processing of these datasets (Combal and Caumont, 2016)[9].

Molthan et al. (2015) used a NASA private cloud sandbox to explore deploying the WRF weather model and to test various system configurations before re-deploying on a commercial cloud for full scale testing. The UK Met Office Visualization Lab does all their work in the cloud and can be thought of as an all-encompassing sandbox. Because of the operational and security requirements of the main Met Office IT infrastructure, the only way they are able to explore cutting edge technologies and applications is by doing all their work in the cloud (Robinson et al., 2016).

The Earth Science Information Partners (ESIP) has created a *de facto* sandbox by creating an organizational account with Amazon Web Services to enable members to start using the cloud painlessly. Hack for the Sea[10] has set up a sandbox for use during their hackathons but also makes it available to a wide variety of marine professionals and non-professionals for cloud compute and storage at greatly reduced cost. Ocean Networks Canada (ONC) has The Oceans 2.0 Sandbox, which is for internal use. The goal of this sandbox is to bring computing closer to the data by making it easy for ONC scientists to upload and use scripts on the same cloud resources where their data reside.

IOOS is creating a Coastal Ocean Modeling sandbox to enable researchers to explore transitioning their models to the cloud. The aim of the sandbox is to make computing resources available and to foster a community

[8]https://www.fgdc.gov/initiatives/geoplatform/geocloud
[9]https://cordis.europa.eu/result/rcn/171980_en.html
[10]https://github.com/hackforthesea/welcome/

of researchers with expertise in migrating models to the cloud and running them there. The sandbox is intended to serve as a transitional location for models that will eventually be run on NOAA/National Weather Service computing resources or NOAA-wide cloud resources and it will replicate the operational computing environment wherever possible.

As more users explore migrating to the cloud, sandboxes will remain an important tool for easing the transition from research to operations and will provide an important place for experimentation and development. They will also be used as a commons to create and nurture communities and as a place to exchange experiences and techniques. Funding agencies and others can provide these sandboxes in the same way they currently provide communication tools and meeting spaces to support projects.

Cloud Providers as an Archive, or an Archive

Archiving – Not Necessarily the End Point

For many projects, archiving is where data are preserved, typically after a project is completed. Many publications or granting agencies require the researchers to archive their data to make them accessible so that others might reproduce research results, or to provide a safe haven for data that are danger due to lack of funds to continue data stewardship or preservation. For others, archives or data repositories are places where collaborators can contribute similar data sets for sharing and curation – the pattern of "management of scientific data" mentioned above. Formal Archives, less restrictive archives, and repositories improve the chances of data being re-used and shared with a wider audience for reanalysis or use in new ways. Cloud computing provides new ways to make archiving work for research and collaboration and the cloud can host new kinds of archives and repositories.

While many researchers provide data to Archives of record National Archives and Records Administration (NARA) or specialty federated archives, the cloud allows for new groups and collaborators to build archives or repositories using commodity cloud with less oversight and levels of governance. While this seems contrary to the idea of a formal Archive, new tools and certifications developed by data management communities can give data providers considering submitting data a sense that the archive has been vetted, evaluated and made trustworthy for data submission and download. One example of this is the World Data System's Core Trust Seal certification process. This organization has certified repositories for their ability to steward, curate, and provide data submitters and providers with open data access in a reliable manner for a long-term stewardship.

Addressing Storage and Accessibility

Enterprise data management has long used physical offsite data storage as method of data protection. Deploying data into the cloud uses the same concept but can be spun up quickly and can scale up storage and access to fit the needs of the users. Data retrieval can be slower for off-premises backups because data providers/enterprises may have written the data to tapes or other media which are slower to access or a user may have chosen deep storage in the cloud.

Cloud storage companies realize that not all data are created equal. Some data sets may not be accessed after archiving as often as others, based on the content, size and other means of data access. Variations in data storage choices are given names which allude to how the data are accessed – e.g., data storage that is hot or near, would be data accessed more frequently than data storage with names like cold or glacier storage which are for infrequently accessed data. In some cases, historical data sets that need to be archived to fulfill a mandate do not require direct read access and can be put into a deeper level of archive. For other data sets used by multiple collaborators which are still being analyzed or curated (metadata improved, error checked), the nearby or hot storage options makes sense. Costs of archiving data (and subsequent access) vary based on the storage decisions made by the data management mandates and colder storage typically costs less than warmer. Analytics on data access, user behavior modeling and download versus data browsing may help cloud engineers and data providers determine when to shift data sets from deeper colder storage to a warmer storage. This may be event-based (extreme weather-based reanalysis of data or new/older operational instrument comparisons). This also allows data managers and cloud engineers to estimate and budget for shifts in the archival access loads based on data usage. Data virtualization, used by commercial entities, is another method to keep down cloud costs – the data sets that are larger, and not used often, can be virtualized and produced on demand when needed, saving storage costs.

For many, the startup cost for archival storage and access may seem high, but prices continually come down and are dependent on the access requirements. Not having to purchase on-premises hardware should bring the costs down and as data volume increases and the capacity of data center does not increase as quickly, cloud archival storage makes more sense.

NASA EOSDIS – Cloud Archiving

NASA's Earth Observing System Data and Information System (EOSDIS) project has recently moved their data stores to the cloud (EOSDIS, 2018). The project includes earth observational data sets from several distributed active archives for users in the scientific community. The arguments for moving into the cloud are not so much that cloud resources are less expensive than the traditional on-premises data storage and archiving solutions, but that by putting the archival stores in the cloud, these data sets are closer to the cloud-based compute power that many using earth science resources require. There is no longer the need to download data to one's desktop to do complex analysis; the data, computation, analytics, and visualization are all in one place.

Challenges to Using the Cloud for Archiving

Success of projects like EOSDIS for cloud archiving may lead to other distributed archives prototyping projects to test the efficacy of cloud storage as a way to provide data archiving as a service (DAaaS), but issues around data stewardship, certification, data retention policies and data governance may need to be addressed prior to transitioning from traditional archiving models.

Best practices around data archiving recommend that data formats for archiving be open and well-documented – flat files, simple geospatial files and JSON objects that are easily described and machine and human readable. While this makes sense in a traditional archive, these formats are not natively cloud friendly due to inefficiencies in reading large files in these formats. This may require a shift by data managers and archivists in what they are willing to archive or require an extra step to transform data to make it more cloud amenable.

The long-term storage of data as NOAA acquires commercial cloud infrastructure requires consideration of the long-term viability of the cloud provider. NCEI considers long-time storage of data to cover a period of 75 years. It is very likely that the business model of the cloud provider will change over this period. This may affect the costs and benefits of cloud-based storage. Similarly, the underlying data storage technology will most likely change over this period. Scientific data archive centers that act on behalf of future generations of scientists, should consider deep local storage of a verified "master" copy of data.

PREPARING FOR THE NEXT WAVES OF USERS, TECHNOLOGIES, AND POLICIES

The technical changes we have discussed are paralleled by human changes. In the past, marine research was mainly hands on – researchers went out and collected samples or measurements while on a cruise. As Kintisch (2013) has observed, graduate students are now less likely to ever go to sea – they are working with satellite data, model outputs and aggregated datasets. Research groups have become virtual (Robinson et al., 2016; Wigton, 2016) and an entire research program can be conducted in the cloud – from communication to gathering data to analysis and the distribution of results. It behooves us to consider the human dimensions of cloud adoption as well as the technical strengths and weaknesses of the cloud.

TABLE 1 | Waves of ocean data users and developers.

Wave	Connectivity	Work patterns and needs	Technology best practices that reflect their work patterns and information needs
The Future	Always online, always connected	Understand continuous information, less interested in data that produced the information Less likely to understand or be interested in the *entire workflow* rather they will focus on aspects of it: analysis, visualization relevance and context of mashing up a variety of information sources. Challenge will be ensuring that the information they receive still supports deep science	Expectation of immediacy and continuous connectivity to information Not tolerant of long processing times or difficulty in getting an answer to their question Demand speed of cloud or edge computing
Digital Nomads	Connect from anywhere, applications centric	Understand continuous data collection, require information Comfortable with technology and view it as extension of themselves. Digital Nomads have a different relationship with information than technical or research users?	May be frustrated by organizational inertia when it comes to adopting, leveraging and embracing the Cloud
Technical Experts	Hard core large pipeline connectivity	Understand entire workflow – sensor to results Want to know the details of what they are doing, are inclined to make updates and fixes themselves, and want to know the path of data from observation to use. They are very familiar with the conversion of data to information and intimately understand every nuance of that conversion	Well documented workflows in the cloud can enable them to share techniques and standardize paths. Need high capacity (cloud) computing resources and fast connectivity
Researchers	Lighter connectivity to the Internet	Understand final results of data processing and expect quality data. Want to use data and need to be able to trust their quality but may not want to know all the details. They may be comfortable with a reliance on the automatic conversion of data to information	Need trusted data in the cloud and efficient, expandable and easily shared analysis and visualization tools Need high capacity (cloud) computing resources and fast connectivity
Digitally divided	Limited connectivity – either permanently or situational	Need information but may not have access to HPC etc. May be members of other waves working as first responders during disasters or at sea Need information and require technologies that will enable them to mitigate issues such as low bandwidth or missing or destroyed communication infrastructure	Need cloud-based technologies that support intermittent connectivity and asynchronous communication. Need trusted data in the cloud and efficient, expandable and easily shared analysis and visualization tools

As we look at the factors and variables affecting the move of organizations to the Cloud for storage, resources, processing, and security, it is important to recognize the bi-directional impact of the next waves of users. Individual and institutional attitudes are shifting, prompting a new wave of Cloud users (**Table 1**). Many have never known a professional or personal environment without the concept of being "online." They are mobile-savvy, always connected, hyper-aware of shifting technology trends and readily willing to adopt emerging technology. Organizations should adopt best practices that reflect their work patterns and information needs, guaranteeing a much higher likelihood of their adoption and continuation of the data science integrity that is a core trait of the ocean science community.

A Technological (R)evolution

A technology evolution is equally underway and it will dramatically affect ocean science and the Cloud. Autonomous vehicles, swarm robotics, Edge computing (aka sensor-based computing), *in situ* communications such as cabled observatories, and global availability of low cost, high bandwidth communications will disrupt ocean data collection and distribution. Data will be processed at the source of collection, sensors and vehicles will autonomously make decisions based on that processed data, science-based machine learning[11,12] and the results will be broadcast in near-real time once the sensor is able to contact the Internet. Consumers will be a mix of human and machine end-points.

Future users will enjoy a near continuous Internet experience for non-submerged devices and cabled observatories and the human and non-human consumption of the information that they generate. The emerging Ambient Internet will see the Internet effectively disappear as it becomes connected to nearly everything, and in particular, devices, vehicles and sensors used for marine data collection. This will naturally lead to more data being collected. We are already nearing a tipping point of data volumes exceeding the human capacity to process it all. Automated and cloud-based processing have been slow to materialize in this industry, and what is likely to happen is that it will be eclipsed by sensor-based processing.

Edge computing sits squarely in the realm of the Ambient Internet, leveraging machine learning, artificial intelligence, advanced processing and computing power on the devices themselves and communicating securely and selectively with the Cloud for data transfer. Human reliance on the raw data itself will depreciate over time as the volume of collected data becomes untenable. Confidence levels will increase as machine-learning algorithms consistently produce better results. There will be a nexus when confidence in machine based acquisition, processing and delivery of information exceeds that of the human equivalent.

Tension Between the Current and the Future

As use of the Cloud becomes more widespread, a natural tension between users of local resources and cloud users will be created. Early adopters should feel compelled to prepare best practices to ease adoption for future waves of users. Some of these include embracing the notion of true Digital Nomads. They will not be beholden to any particular platform, operating system, application or physical space. They will have never known an Internet that was not in their pocket, available to them at all times, without constraint. Their expectations of immediacy will be unparalleled and is not centric to the data itself, but rather to the information that it possesses. The emerging Future wave is going to be comfortable with artificial intelligence and augmented reality with a blurred line of information derived from humans or machines. They will live and work in a world of *augmented intelligence*, where artificial intelligence, machine learning and deep learning assist the human experience.

The behavioral characteristics of the next wave(s), coupled with mainstream information technology and the inevitable reduction in cost and increase in proliferation of smart enabled marine based sensors, will cement the fundamental shift in data-information relationships. Sensor based processing with *results* transmitted to the Cloud will force emerging ocean knowledge workers to have an *information* centric mindset rather than a *data* centric one. This mindset will make it easier for others to receive the information they need without needing access to massive datasets. Cloud hosted weather models are a prime example where advances led by Technical Experts and Digital Nomads can benefit Researchers and the Digitally Divided.

Relevance to Cloud and Policy Today

Creation of the structures needed to support the work of all of the waves to do their jobs and advance ocean science is multi-faceted and need not be considered a monumental effort. Evolving and adapting the current mindsets around the Cloud, Edge computing, artificial intelligence, machine learning and augmented reality will dramatically alter the landscape for future workers. Engaging with industry, both traditional and non-traditional, will help spur the innovation. It will also significantly enhance the quantity and quality of data that is collected as the private sector works to produce more inexpensive and more capable devices that work in a connected world.

Data policies also need to shift. Following the old mantra of "collect it, process it, publish it and store it" will not work in an environment of constantly updated information, huge data volumes and increased access through widespread and continuous Internet coverage. Although data security will remain highly important, there will be demands to make data more available so non-human means can interrogate it, learn from it and apply those results to data banks of valuable information. These approaches need to percolate through all levels of organizations in order to create a culture of innovation and preparedness.

Few would disagree that there is an enormous brain-trust resident in organizations all over the world. Intricate knowledge of data formats, sensor types, performance nuances, and metadata standards (or lack thereof) are just some of the elements. There needs to be a concerted effort to increase

[11] https://ieeexplore.ieee.org/document/7959606

[12] https://www.hydrol-earth-syst-sci.net/22/5639/2018/

documentation, standardization and openness in multiple areas in order to propagate and persist this knowledge.

New commercial opportunities may develop that focus on supporting new waves of workers. Encouraging proposals, new grants, funding for innovation and joint partnerships that stimulate research, commercialization and productization of emerging technology are a beginning. Existing companies also have an opportunity to embrace open data and standards, develop automated processing and better support Edge devices as they come online.

The transformation that is occurring does not just involve the Cloud. It is part of a larger technology movement for smarter, smaller and more computing power all around us. The Cloud is only one piece of the transformation and remaining focused on the Cloud at the expense of Edge computing, smart devices, artificial intelligence, automated processing and information centric workflows will not adequately prepare for the next waves of marine scientists. The combination of people, process, and technology – including the Cloud – must be interfaced effectively to develop ocean data and information systems necessary to observe and predict our oceans, lakes and coasts of the future.

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REVIEW
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Going Beyond Standard Ocean Color Observations: Lidar and Polarimetry

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Passive ocean color images have provided a sustained synoptic view of the distribution of ocean optical properties and color and biogeochemical parameters for the past 20-plus years. These images have revolutionized our view of the ocean. Remote sensing of ocean color has relied on measurements of the radiance emerging at the top of the atmosphere, thus neglecting the polarization and the vertical components. Ocean color remote sensing utilizes the intensity and spectral variation of visible light scattered upward from beneath the ocean surface to derive concentrations of biogeochemical constituents and inherent optical properties within the ocean surface layer. However, these measurements have some limitations. Specifically, the measured property is a weighted-integrated value over a relatively shallow depth, it provides no information during the night and retrieval are compromised by clouds, absorbing aerosols, and low Sun zenithal angles. In addition, ocean color data provide limited information on the morphology and size distribution of marine particles. Major advances in our understanding of global ocean ecosystems will require measurements from new technologies, specifically lidar and polarimetry. These new techniques have been widely used for atmospheric applications but have not had as much as interest from the ocean color community. This is due to many factors including limited access to *in-situ* instruments and/or space-borne sensors and lack of attention in university courses and ocean science summer schools curricula. However, lidar and polarimetry technology will complement standard ocean color products by providing depth-resolved values of attenuation and scattering parameters and additional information about particles morphology and chemical composition. This review aims at presenting the basics of these techniques, examples of applications and at advocating for the development of *in-situ* and space-borne sensors. Recommendations are provided on actions that would foster the embrace of lidar and polarimetry as powerful remote sensing tools by the ocean science community.

Keywords: ocean color, lidar, satellite, profiles, polarimetry

INTRODUCTION

Since the inception of ocean color satellite observation systems, remote sensing has been based on measurements of the radiance emerging at the top of the Ocean color remote sensing utilizes the intensity and spectral variation of visible light scattered upward from beneath the ocean surface to derive concentrations of biogeochemical constituents and inherent optical properties within the ocean surface layer. Passive ocean color space-borne observations began in the late 1970s with the launch of the CZCS space mission. An uninterrupted record of global ocean color data has been sustained since 1997 (thanks to SeaWiFS, MODIS-AQUA, MERIS, VIIRS and OLCI sensors) and will continue at least until 2035 with the NASA/PACE and ESA/Sentinel-3 space missions. These passive observations have enabled a global view of the distribution of marine particles [phytoplankton, total suspended matter (TSM) and colored dissolved organic matter (CDOM), McClain (2009)]. However, these measurements are limited to clear sky, day-light, high Sun elevation angles, and are exponentially weighted toward the ocean surface. Moreover, the processing of the ocean color images requires the knowledge of the atmospheric components (gases, air molecules and aerosols). This step can induce errors (IOCCG, 2010; Jamet et al., 2011; Goyens et al., 2013 among others). Only non- or weakly-absorbing aerosols are accounted for, preventing monitoring some areas over long periods (dust over West coasts of Africa and Arabian Sea; pollution over East coasts of US and coasts of China).

Observations of aerosols use different passive and active remote sensing techniques that could be applied to the ocean for better characterizing the hydrosols and also to improve the atmospheric correction processing. Among those techniques, two are very promising: polarimetry and lidar (Neukermans et al., 2018).

While the spectral radiance is sensitive to absorption and scattering properties of the constituents within the water column, polarized light emerging from the Earth system carries a plethora of information about the atmosphere, ocean, and its surface that is currently underutilized in ocean color remote sensing. Polarized light originating from below the ocean surface contains microphysical information about hydrosols such as their shape, composition, and attenuation, which is difficult if not impossible to retrieve from traditional scalar remote sensing alone. Additionally, polarimetric measurements can be utilized to improve the characterization and removal of atmosphere and surface reflectance that confounds the ocean color measurement. Optical polarimetric remote sensing methods have been extensively used to study the full characteristics of the microphysical properties of suspended particles in the atmosphere, namely aerosols and cloud droplets. The development of sensors capable of measuring and quantifying the polarization characteristics of light scattered by the atmosphere-ocean (AO) system is becoming increasingly important and is opening a new frontier for understanding climate variables. Several space agencies worldwide, including the National Aeronautics and Space Administration (NASA), Centre National d'Etudes Spatiales (CNES), European Space Agency (ESA), and Japanese Aerospace Exploration Agency (JAXA), have launched space observing polarimetric instruments to study aerosols and clouds. These efforts include NASA APS instrument oboard the Glory mission (Mishchenko et al., 2007), the CNES POLDER/PARASOL satellite instruments (Fougnie et al., 2007), and JAXA's SGLI on board GCOM-C (Honda et al., 2006). The aerosol and cloud science communities make increasing use of polarimetric remote sensing to constrain atmospheric particle properties of importance to climate and radiative forcing (Riedi et al., 2010; Dubovik et al., 2011; Hasekamp et al., 2011; Lacagnina et al., 2015; Marbach et al., 2015; Wu et al., 2016; Xu et al., 2016, 2017), but application to ocean color science has been limited, despite a long history of sporadic research in this area. Waterman (1954) was the first to study the underwater polarization as a function of illumination and viewing geometry, while Ivanoff et al. (1961) showed a high degree of polarization in clear ocean waters. It was decade later that Timofeyeva (1970) first demonstrated a decreased degree of polarization in more turbid waters, based on laboratory measurements. Kattawar et al. (1973) pioneered the vector radiative transfer simulations of a coupled atmosphere-ocean system, and 30 years passed before Chowdhary et al. (2006) first modeled the polarized ocean contribution specifically for photopolarimetric remote sensing observations of aerosols above the ocean (Chowdhary et al., 2012), after which interest in ocean applications intensified. Chami (2007) has shown the potential advantage of utilizing polarimetry in understanding the optical and microphysical properties of suspended oceanic particles (hydrosols), based on Radiative Transfer (RT) simulations. Tonizzo et al. (2009) developed a hyperspectral, multiangular polarimeter to measure the polarized light field in the ocean accompanied by an RT closure analysis validating the theoretical analysis. Voss and Souaidia (2010) were able to measure the upwelling hemispheric polarized radiance at several visible wavelengths showing the geometrical dependence of polarized light. Adams et al. (2002) did a closure study in which they matched the measured polarized radiance in clear Mediterranean waters with Monte Carlo RT simulations employing a simple ocean-atmosphere optical model. Although practical utilization and field measurements of the ocean polarized light to retrieve ocean inherent optical properties (IOPs) have been limited, a plethora of theoretical RT models have been developed and utilized for research. Several fully coupled vector radiative transfer (VRT) models that can simulate photopolarimetric radiative transfer through the atmosphere and ocean and across the interface have been constructed and are in current use. These VRT models use various schemes such as Monte Carlo (Kattawar et al., 1973; Cohen et al., 2013), Adding-Doubling (Hansen and Travis, 1974; Takashima and Masuda, 1985; Chowdhary et al., 2006), Discrete Ordinate method (Stamnes et al., 1988; Schulz et al., 1999), Successive Order of Scattering (SOS) (Ahmad and Fraser, 1982; Lenoble et al., 2007; Zhai et al., 2009), Markov chain (Xu et al., 2011) and Multi-Component Approximation (Zege et al., 1993). The 3 × 3 approximation in VRT can be used to accurately simulate the reflected and transmitted total radiance, I, and the polarized radiances Q and U in the atmosphere-ocean system for an unpolarized source such as the Sun (Hansen, 1971; Stamnes et al., 2017). More details are provided in section Polarimetry Technique.

Lidar is the acronym of Light Detection and Ranging. Lidar is a "laser radar" technique that has been used for a wide range of atmospheric applications (Measures, 1984; Weitkamp, 2006) including measurements of aerosols, clouds, atmospheric trace gases and surface elevation. For ocean applications, lidar has been mainly employed from aircraft (Churnside, 2014 and references within). Lidar allows the estimation of the shallow water depth along coastal waters with a high accuracy and high spatial density features (Guenther et al., 2000; Hiddale and Raff, 2007; Bailly et al., 2010). Lidar also has a better penetration into the seawater, up to three times that of passive sensors (Peeri et al., 2011). Abdallah et al. (2013) studied two scenarios for spaceborne bathymetric lidar: an ultra-violet (UV) lidar and a green lidar. Their waveform simulations showed that the bathymetry detection rate at a 1 m depth varied between 19 and 54% for the UV lidar and between 0 and 22% for the green lidar depending of the type of waters. They also showed that the lidar accuracy, when the depth is detected, was around 2.8 cm. Lidar has been widely used for fisheries. The first detection of fish schools was shown by Murphree et al. (1974), followed by several additional studies (e.g., Squire and Krumboltz, 1981). Airborne (Vasilkov et al., 2001) or ship-borne lidar (Bukin et al., 2001) have been also used to detect scattering layers over the depth. It is also a very promising technique for the estimation of the sea temperature profiles using either the Raman or the Brillouin scattering (Leonard et al., 1979; Rudolf and Walther, 2014 and references within) but these studies were either theoretical development or laboratory tests. As the lidar equation (section Basics of Lidar) is a function of the scattering and absorption coefficients of the marine particles, it is therefore possible to detect the optical properties of the seawater (Churnside et al., 1998; Montes et al., 2011). More detailed examples of the use of airborne lidar in oceanic applications is shown in section Polarization Lidar.

Despite the oceanic applications of lidar (as shown previously and more in details in section Lidar technique), this active remote sensing technique has not received significant attention from the ocean color remote sensing community. Several reasons can explain this: cost and size of the instrument, lack of sampling swath, few wavelengths, etc. However, this technique has regained interest from the ocean community in the past years. New studies used the lidar signal from the space-borne CALIOP instrument on-board CALIPSO to estimate particulate backscatter (Behrenfeld et al., 2013, 2017; Churnside et al., 2013; Lu et al., 2014) and show that the lidar signal from CALIOP provides accurate estimates of this parameter over the globe. However, the CALIOP instrument was not designed for ocean applications and its coarse vertical resolution makes the retrieval of vertically-resolved ocean properties challenging. In addition, the standard backscatter technique employed in CALIOP does not enable the separation of vertical variation in absorption and from that of scattering. New technologies such as the High-Spectral Resolution Lidar (HSRL; Hair et al., 2008, 2016; Hostetler et al., 2018) can help to overcome this issue [section High-Spectral-Resolution Lidar (HSRL)].

Presently, there is a major need to develop a lidar and polarimetry ocean community with access to ship and/or aircraft *in-situ* instruments. There is also a major need to develop outreach and education programs (e.g., through summer schools and curriculum) to develop a new generation of remote sensing scientists and engineers trained in lidar and polarimetry techniques (section Outreach and Education). Two main summer schools are organized for Msc/PhD students and early career scientists working on ocean color (University of Maine and IOCCG, respectively). However, no specific or polarimetry courses are included in their curriculum. This is mainly due to lack of available instruments and scientists being able to teach oceanic lidar.

In this review, polarimetry and lidar are presented for applications in ocean into two separate sections, with their theoretical description followed by examples of results. A third section shortly presents the need in term of education and outreach.

LIDAR TECHNIQUE

Basics of Lidar

Oceanographic lidars can be configured to implement several different measurement techniques (described below) but all rely on the same basic principle of operation (see, for instance, Hoge, 2003, 2005; Churnside, 2014; Hostetler et al., 2018). A laser transmitter emits a short (e.g., 10 ns) pulse of light into the water. This light pulse interacts with the marine particles (water molecules, phytoplankton, suspended particulate matter) in ways that either scatter the transmitted photons or generate photons at different wavelengths through absorption and re-emission. A small portion of these photons travel backward toward the lidar where they are collected by an optical telescope. Optical components downstream of the telescope collimate the received light and optically separate it into various optical channels as dictated by the particle technique being implemented. Optical detectors and signal processing electronics respond to the received optical power and convert it to a digital signal, which is recorded as a function of time from the initiation of the laser pulse. The time-of-flight ranging technique is used to convert this time-profile into a profile as a function of range or depth: i.e., the "clock" starts at the initiation of the laser pulse, and the distance that photons have traveled is determined by the speed of light; photons arriving later come from greater distances than photons arriving earlier. The range resolution of a lidar profile is determined by the rate of sampling by its detection electronics: the higher the rate, the higher the range resolution. Oceanographic lidars are typically operated in a nadir or near-nadir pointing geometry such that they provide depth-resolved profile information.

The most common laser source is the Q-switched, frequency-doubled Nd:YAG laser, operating at 532 nm. This wavelength is chosen due to the robustness of available lasers, not as the optimum wavelength for ocean remote sensing. Gray et al. (2015) characterized the benefits to use a multi-wavelength lidar (470/490 nm and ∼570 nm) for improving depth penetration with wavelengths.

In-situ Lidar

By "*in-situ*" marine lidars, we refer to lidars that are operated below the sea surface (in-water) or just above (above-water) it from ships or other marine vehicles. Advances in lidar technology, making it more and more rugged, compact, energy efficient, and inexpensive, have increased the use of *in-situ* lidar in marine studies. Regular deployment of these systems on a variety of platforms becomes increasingly practical, allowing for continuous remote sensing of the vertical and horizontal distribution of particles in the ocean. Some basic requirements of *in-situ* marine lidars include the following.

1. A watertight, compact, modular and mechanically robust enclosure system to protect optical and electronic components from water and sea salt.
2. A rugged, vibration-insensitive laser transmitter that can operate under the required environmental conditions (e.g., variation in temperature) and a structure that can insure maintenance of transmitter-to-receiver alignment.
3. A receiver with optical filtering bandwidth and stability required and to spectrally select the return signals of interest (this can be done through interference filters as well as spectrometers or interferometers, depending on the required spectral resolution). For ocean lidar applications, a large detection dynamic range is required (for fluorescence applications (described below) this is not as critical). Finally, a high signal sampling rate is required when small/vertical-scale structures are to be investigated.

Depending on the objectives of the particular application, the *in-situ* lidar systems constructed and deployed can satisfy the aforementioned requirements to a different extent. Typically, the *in-situ* lidar configurations can be identified on the basis of the interaction between radiation and matter used by the lidar systems. The mostly common configurations are: (1) Elastic backscatter lidar and (2) Light Induced Fluorescence lidar. We also present some results from newer multi-spectral lidars.

Elastic Backscatter Lidar

The lidar equation of an elastic backscatter lidar (EBL) is as follows (Churnside, 2014):

$$S(z) = \frac{EAO(z)\, T_0 T_s^2 \eta \nu}{2n\,(nH+z)^2} \beta(\pi, z) \exp\left[-2\int_0^z \alpha(z')\, dz'\right] + S_B \quad (1)$$

where S is the detector photocathode current, E is the transmitted pulse energy, A is the receiver area, O is the lidar overlap function (also known as the geometric form function), T_O is the transmission of the receiver optics, T_S is the transmission through the sea surface, η is the responsivity of the photodetector (Ampere.Watts^{-1}), n is the refractive index of sea water, ν is the speed of light in vacuum, H is the distance from the lidar to the surface (height of the aircraft for near-nadir airborne systems), z is the path length in water (depth for near-nadir airborne systems), β is the volume scattering coefficient near a scattering angle of π radians, α is the lidar attenuation coefficient, and S_B is the photocurrent due to background light.

Only research lidars are available for ship-borne applications (in- or just above-water) and the early versions were mainly proof-of-concept. However, EBL are now on the market as industrial products for atmospheric applications (for instance, Matthais et al., 2004). They are rugged, compact and can work autonomously with very little human attendance. Two main types of EBL instruments are available.

- The first type is based on the classical approach, using high power laser, low repetition rate. Typical specifications are: 10–100 mJ per pulse, at 10 to 100 Hz. The lasers are solid state laser, using flash lamps and water cooling. These systems are not eyesafe and so need qualified people to use them. These systems work very well for laboratory applications or very short campaigns but cannot be deploy easily in the field.
- The second type is based on the micropulse lidar (Welton et al., 2001). The typical specifications are: 5–50 μJ, 1 to 400 kHz. The laser are diode-pumped solid state laser (or even pulsed laser diode directly). The systems are usually quite compact compared to standard systems. They can emit laser pulses in eyesafe regime and need no special qualified people to install and operate them. Because of the much lower energy, they work at high repetition rate to get equivalent Signal to Noise Ratio (SNR) as the standard approach.

These two standard approaches can be used with single wavelength emitting source, giving only range corrected signal or with multiple wavelength systems, providing profiles of diffuse attenuation (K_d) and particle backscatter (b_{bp}). Multiple emission and reception channels are more complex systems to operate and to maintain because of their size and cost. No EBL for oceanic applications is commercially available but the required technology is readily available.

EBL has been used for several oceanic applications for the past 20 years. For instance, Reuter et al. (1995) developed a shipboard lidar for the estimation of the concentration of chlorophyll-a concentration and sediments and made measurements in the Atlantic ocean. Numerous depth profiles were obtained along the ship track with a resolution of 0.5 m, with penetration depths up to 40 meters. The authors detailed the design of the instrument which was mounted on the ship hull. The same type of deployment has been used by Bukin et al. (2001) to measure the space-time distribution of the optical characteristics in oceanic light scattering layers. They showed that their approach allowed the investigation of dynamic processes in the upper ocean layer. Lately, Collister et al. (2018) developed a polarized lidar to measure laser backscattering and linear depolarization profiles. A useful aspect of this lidar is the ability to deploy it in the water (1-m depth). Doing so provides the advantage of avoiding the specular reflection of the sea surface in the received signal, which can create transient artifacts in detected signals, but this type of deployment is possible only at fixed stations rather than in continuous underway operations.

Light Induced Fluorescence Lidar

The applications of Light Induced Fluorescence (LIF) through shipborne lidar systems date back to a few decades ago. LIF has an extensive history of providing data for oceanographic research and monitoring, as the detection of oil spills (Pisano et al., 2015; Babichenko et al., 2016) and other pollutants (Barbini et al., 1999), quantification and characterization of phytoplankton and CDOM (Palmer et al., 2013), as well as the estimation of TSM (Aibulatov et al., 2008). LIF Lidar datasets have also successfully served as validation for satellite-derived oceanographic measurements (Fiorani et al., 2004, 2006). The fluorescence echoes from UV excitation assume a direct correlation with the concentration of the chromophore molecules contained in the excited target (Hoge and Swift, 1981). Hence, the fluorescence of chlorophyll-a allows an indirect measurement of phytoplankton biomass, while estimates of CDOM, also known as yellow matter, becomes important for the knowledge of marine ecology, and is a complex mixture of water-soluble organic substances including mainly humic and fulvic acids. Crude and refined oils may also be and refined oils may be investigated LIF lidars. However, the fluorescence bands of such compounds usually lie in the UVB-UVC spectral regions (<300 nm), and this requires excitation wavelengths shorter than 300 nm. Usually Nd:YAG lasers (with fourth harmonic at 266 nm) are employed, because of their compactness, reliability, and ease of operation.

The intensity of the detected signal depends on several system parameters: the optical extinction of the crossed media at the emitted and fluorescent wavelengths (λ_{em} and λ_{fl}, respectively); the optical properties of the considered chromophores (Reuter et al., 1993); the power of the emitted radiation; the optical efficiencies of the system at the selected wavelengths.

Usually, the fluorescence signal is not time-resolved, since the extinction in seawater is quite high for UV radiation, so that just a few meters can be probed. Also, fluorescence decay times (typically of the order of some ns) limit the resolution to the order of 1 m, and the small fluorescence cross section makes it hard to achieve a good signal to noise ratio for small integration volumes. The strategy is rather to integrate the signal over the column and to determine the average fluorescence signal, which must be calibrated against a reference measurement.

The typical instrument design of a LIF lidar includes a frequency tripled Nd:YAG transmitter laser emitting at 355 nm, a telescope collecting the return signals of interest and an optical unit dedicated to the discrimination of the different signals (e.g., inelastic backscattering returns coming from CDOM at 450 nm, Chla at 685 nm, and the water Raman backscatter signal at 404 nm). As mentioned before, for oil detection a shorter wavelength excitation is necessary (i.e., quadrupled Nd:YAG at 266 nm), since the fluorescence bands used for discrimination fall below 300 nm.

LIF can also be stimulated using frequency-doubled Nd:YAG lasers emitting at 532 nm, revealing fluorescence of chlorophyll-a present in almost all marine algae (∼670–690 nm), the distinct phycobiliprotein fluorescence of cyanobacteria and red algae (∼540–595 nm), and water Raman scattering (∼645 nm) (Hoge and Swift, 1981). Using short-pulse pump-and-probe excitation protocols at 532 nm, the variable fluorescence of chlorophyll-a was used to study the photochemical characteristics of phytoplankton from an airborne lidar (Chekalyuk et al., 2000), but there is no reason this could not be accomplished by *in-situ* LIF lidar.

Raman and fluorescence signals are limited by the small cross sections of both processes and parasite signal contamination. In the marine environment, these limitations are stressed by the seawater light absorption and sometimes by the strong return signal due to the Fresnel reflection from the air/water interface or sunlight reflection inside the field of view of the instrument. However, median filters can help overcoming these problems. These constraints imply the employment of cutting-edge optical components with strict conditions on the spectral selection of the return signals.

Multispectral Lidar

In-situ Lidar technology can exploit the spectral reflectance properties of oceanic biogeochemical constituents. Both elastic and inelastic reflectance properties can be used for phytoplankton taxonomic identification, colored dissolved organic matter chemical species identification and transformation, and assessing particle size distribution. As discussed above, fluorescence lidar with one or more excitation wavelengths can be used to sample the emission spectra of various optical constituents.

Using 473 and 532 nm microchip pulsed lasers, a lidar payload designed for small autonomous underwater vehicles (AUV) deployment uses narrow field-of view receiver channels at each wavelength to estimate range-resolved water column attenuation, and backscattering coefficients (Strait et al., 2018). These results suggest that a time/range-resolved differential absorption lidar (DIAL) approach can be used to resolve water column bio-optical components. DIAL has been developed to detect concentrations of atmospheric gas. The simplest DIAL algorithm examines the ratio of the received power from laser pulse trains at two wavelengths. If the absorption coefficients of the studied gas are known at the two wavelengths, it is possible to estimate the gas concentration for the range interval (Browell et al., 1983).

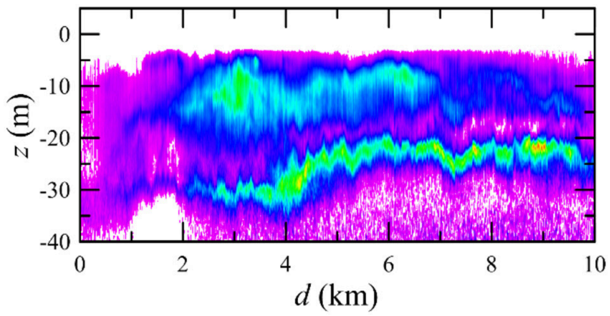

FIGURE 1 | Cross-polarized lidar return from phytoplankton layers in the NE Pacific Ocean as a function of depth, *z*, and distance along the flight track, *d*. The color represents the intensity of the lidar signal. Reuse with permission from Churnside and Donaghay (2009).

The same DIAL equations can also be used to detect soft (macro)algal targets on benthic or cryospheric (ice bottom) substrates, e.g., from a lidar mounted on an AUV. Rehm et al. (2018) show the ability to detect a soft macroalgal target at 10 m (*Sargassum* sp.) using this differential absorption approach.

Airborne Lidar

Polarization Lidar

The simplest lidar configuration consists of a polarized laser transmitter and two receivers that are sensitive to the co-polarized return and the cross-polarized return. Alternatively, the first channel can be unpolarized to more readily combine with ocean color data. In either case, a lidar can be assembled from commercial components and can operate from a small aircraft. Depth resolution is generally <1 m. In clear waters, a simple lidar at 532 nm can penetrate to >50 m. Penetration is less in more productive coastal waters (penetration to $3/K_d$ is a good rule of thumb, where K_d is the diffuse attenuation coefficient at the lidar wavelength), but these waters are also more interesting in terms of ocean ecosystem health and biodiversity. For this type of study, the cross-polarized return is particularly useful (**Figure 1**), because the co-polarized return includes contributions from the surface specular return, bubbles, and water in addition to the biological contribution.

In a quasi-single-scattering approximation, the depth-dependent signals from the two channels of a polarization lidar are given by Churnside (2008):

$$S_c(z) = \frac{EAO(z)\,T_0 T_s^2 \eta\nu}{2n\,(nH+z)^2}\beta_c(\pi,z)\exp\left[-2\int_0^z \alpha\left(z'\right)dz'\right]$$

$$S_x(z) = \frac{EAO(z)\,T_0 T_s^2 \eta\nu}{2n\,(nH+z)^2}\left[\beta_x(\pi,z)+2\beta_c(\pi,z)\int_0^z \gamma\left(z'\right)dz'\right] \exp\left[-2\int_0^z \alpha\left(z'\right)dz'\right] \quad (2)$$

where S is the lidar signal (photocathode current) for the copolarized or unpolarized (subscript C) and cross-polarized (subscript X) channels and γ is the rate of depolarization of the light by multiple forward scattering. For an airborne system, it is easy to ensure that $O(z) = 1$ for all depths, leaving four depth-dependent properties of the water (β_C, β_X, α, and γ) to be estimated from these two equations.

Two approaches to retrieval of these parameters from the lidar equations have been considered. The first assumes known relationships between them. For example, the equation for the unpolarized lidar signal can be used to obtain α and β if the ratio of these two quantities can be estimated (Churnside et al., 2014). The second takes advantage of the fact that α and γ are integrated over depth, reducing the effects of small-scale variations. In this approach, an average value for attenuation is obtained and used to produce detailed profiles of scattering (Churnside and Marchbanks, 2015, 2017).

The lidar measurements can often be related to parameters commonly used in ocean color retrievals. For airborne lidar, the lidar-attenuation coefficient is very close to the diffuse-attenuation coefficient, K_d, as long as the laser spot on the surface is large (Gordon, 1982), and this relationship has been verified (Montes et al., 2011; Lee et al., 2013). The most commonly used scattering parameter in ocean color measurements is the particulate backscattering coefficient, b_{bp}. This can be obtained from the volume scattering function measured by the lidar (Churnside et al., 2017a). The contribution to scattering by seawater is well-known and can be removed. Then, an empirical value for the ratio of b_{bp} to the volume scattering function at 180° is applied (Churnside et al., 2017a). This approach seems to work better for single-angle measurements at scattering angles near 120° (Boss and Pegau, 2001; Sullivan and Twardowski, 2009; Zhang et al., 2014), and more measurements at 180° are needed.

Since the first recorded detection of fish by airborne lidar in 1976 (Squire and Krumboltz, 1981), a number of studies have shown that lidar compares well with traditional techniques for fish in the upper 30–40 m of the water column (Churnside et al., 2003, 2009, 2017b; Roddewig et al., 2017). The advantage of airborne lidar for fisheries surveys is that it can cover large areas quickly and at lower cost than a surface vessel. On the other hand, these surveys cannot provide the detailed information that can only be obtained through direct sampling from a vessel. The best solution would be aerial surveys coupled with adaptive sampling by surface vessel. Airborne lidar can also be used to document cases of fish avoiding the research vessel performing the survey.

Lidar has also been used to detect zooplankton. The scattering from zooplankton is generally less than that from fish, and detection is more difficult. For copepods, a combination of thresholding and spatial filter is effective (Churnside and Thorne, 2005). A surface layer of euphausiids was detected, but the zooplankton signal in that case could not be separated from the signal produced by the many predators in the layer (Churnside et al., 2011). Unlike most zooplankton, aggregations of jellyfish can produce very large lidar signals, and airborne lidar has been used to describe the internal structure of aggregations of moon jellyfish (Churnside et al., 2016).

There is often a deep chlorophyll maximum near the bottom of the mixed layer in the ocean (Cullen, 1982; Lewis et al., 1983), and the layers of phytoplankton that make up this maximum have been studied by airborne lidar (Vasilkov et al., 2001; Goldin et al., 2007; Churnside and Donaghay, 2009). Often, these layers are very thin (<5 m) and very intense (>3 times the

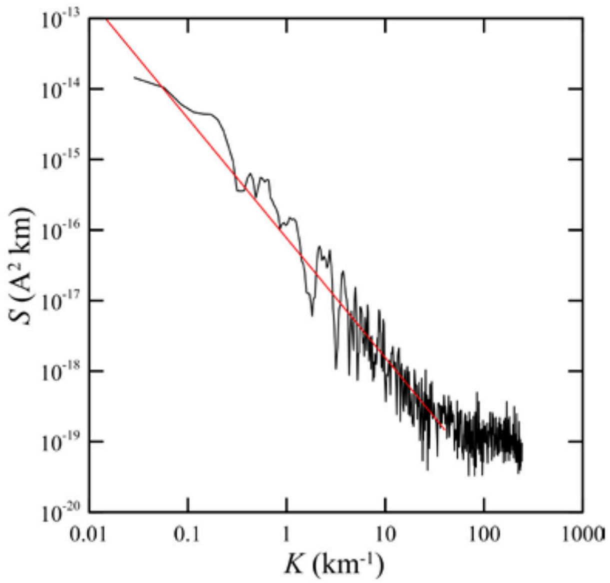

FIGURE 2 | Power spectral density, *S*, as a function of spatial frequency, *K*, for the lidar return from a depth of 10 m across Barrow Canyon, Alaska. Red line is the $K^{-5/3}$ relationship characteristic of turbulent mixing.

background density) (Durham and Stocker, 2011). These intense layers affect primary productivity, since they are often at a depth that optimizes sunlight and nutrient availability. They also affect transfer of energy to higher trophic levels, since grazing efficiency is high within the layers.

Using phytoplankton as a tracer, several important features of upper ocean dynamics can be measured. The first is the depth of the mixed layer when there is a layer at the pycnocline (Churnside and Donaghay, 2009; Churnside and Marchbanks, 2015). The pycnocline is a density gradient, so it will support propagation of gravity waves, known as internal waves. Internal waves are important in that they transfer significant amounts of heat, energy, and momentum in the ocean (Laurent et al., 2012). Large, non-linear internal waves are particularly interesting, because of their ability to propagate over large distances. They are also particularly amenable to characterization by airborne lidar (Churnside and Ostrovsky, 2005; Churnside et al., 2012). Turbulent mixing of phytoplankton can also be identified by a characteristic power law spectrum of number density. **Figure 2** shows a plot of power-spectral density of the cross-polarized lidar return from a constant 10 m depth across Barrow Canyon in the Chukchi Sea west of Utqiaġvik, Alaska. The red line demonstrates the expected $K^{-5/3}$ relationship for more than three decades in spatial scale down to the lidar noise level of about 10^{-19} A^2 km.

High-Spectral-Resolution Lidar (HSRL)

The HSRL technique is similar to the polarization lidar technique described above and HSRL instruments often include separate co- and cross-polarized detection channels. The differentiating feature is the ability HSRL provides for independent, unambiguous retrieval of attenuation and particulate backscatter without external assumptions (e.g., the assumption of ratio of α to β as described above). The technique has been employed for decades for aerosol and cloud studies (Shipley et al., 1983; Piironen and Eloranta, 1994; Esselborn et al., 2008; Hair et al., 2008), and has only recently been applied to ocean profiling. The most common approach involves a single-frequency (vs. multi-mode) laser transmitter and optical elements in the receiver that spectrally separate molecular backscatter from particulate backscatter. This spectral separation hinges on the fact that backscatter from particles is at the same frequency as the transmitted laser light whereas backscatter from water molecules is shifted by several GHz (e.g., $\sim$7 GHz at 532 nm) due to Brillouin scattering processes. The receiver directs the light, either interferometrically or by other means, to separate detection channels that make range-resolved measurements of backscatter as described in the previous sections. In most implementations of the technique, there are two HSRL channels. One channel predominantly measures molecular backscatter and the other a combination of molecular and particulate backscatter. The profile of attenuation is derived from the derivative (with respect to depth) of the natural logarithm of the molecular channel signal. Particulate backscatter is derived from an algebraic combination of the two channels [see Hostetler et al. (2018) for details]. In addition to independent, accurate retrieval of attenuation and particulate backscatter, another powerful feature of the HSRL technique is the ability to maintain calibration through the entire profile. This is particularly important for higher-altitude airborne (and future spaceborne) implementations for which the intervening atmosphere variably attenuates the received ocean signal due to variations in aerosol and/or cloud optical depth.

Airborne HSRL ocean measurements were first conducted by NASA in 2012 on a deployment based in the Azores, which was conducted as a proof-of-concept study. The instrument used on that study, "HSRL-1," operated at 532 nm and employed the iodine filter vapor technique for frequency separation in the receiver. Based on that experience, improvements were made to the lidar and it has since acquired data on several airborne deployments, including the Ship-Aircraft Bio-Optical Research (SABOR) mission in 2014 and three deployments for the North Atlantic and Marine Ecosystems Study (NAAMES) in 2015, 2016, and 2017. The HSRL retrievals of b_{bp} and K_d show excellent agreement with ship-based *in-situ* estimates made on SABOR (Schulien et al., 2017; Hostetler et al., 2018) and satellite ocean color retrievals (Hair et al., 2016). Data from the HSRL-1 are also used to retrieve estimates of both total and particulate depolarization, and those data along with the b_{bp} and K_d profiles are currently being assessed for information on community composition. **Figure 3** shows aerosol backscatter, aerosol optical depth, b_{bp}, K_d, and particulate depolarization retrievals from HSRL-1 on 13 May 2016 NAAMES flight in the Western North Atlantic. These data illustrate the ability of the HSRL technique for providing accurate ocean optical properties despite the high and highly variable aerosol optical depth in the overlaying atmosphere.

From and engineering perspective, the HSRL technique is much more challenging than the standard backscatter and polarization technique described above. In the receiver,

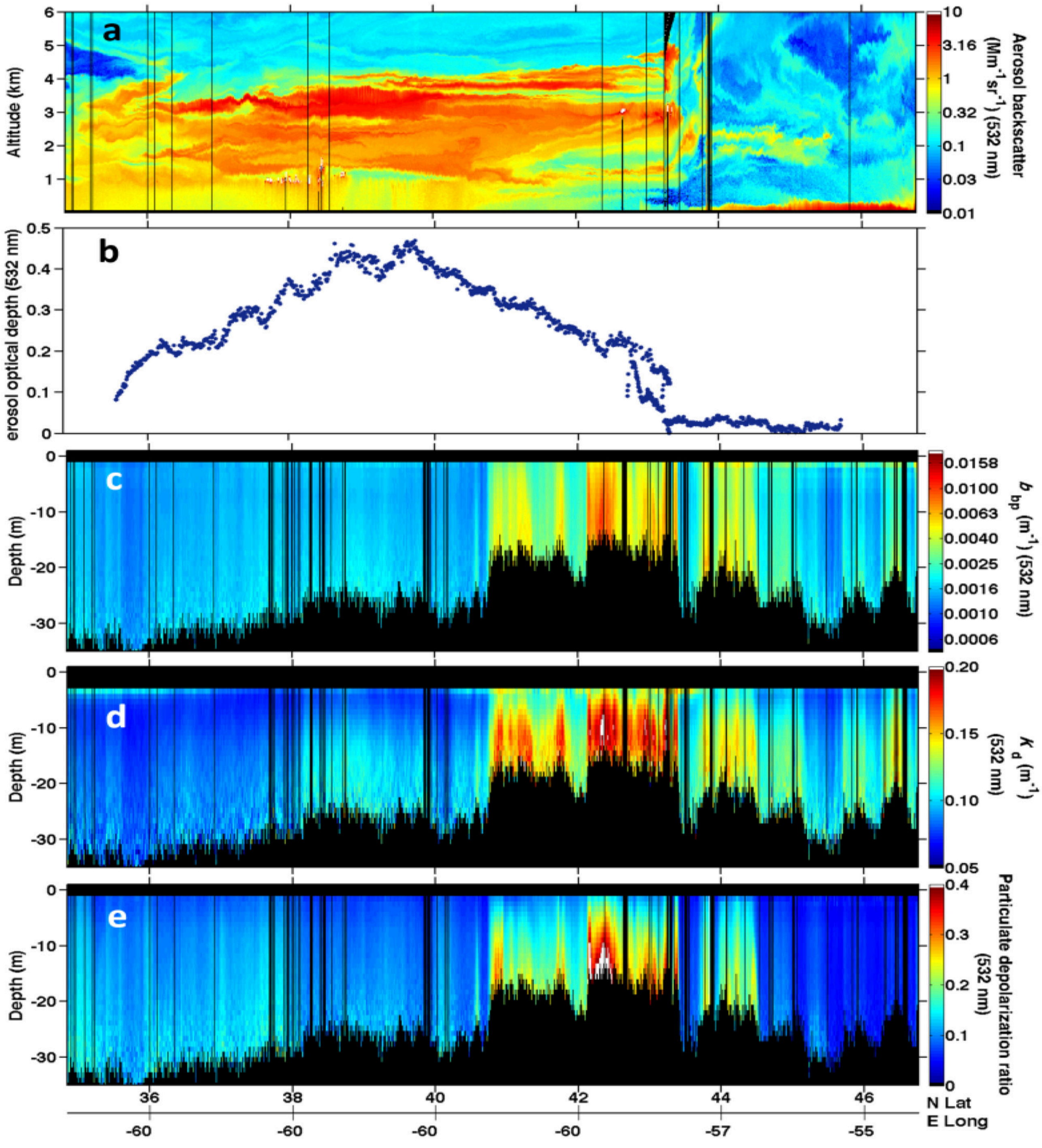

FIGURE 3 | Aerosol backscatter **(a)**, aerosol optical depth **(b)**, b_{bp} **(c)**, K_d **(d)**, and particulate depolarization **(e)** retrievals from HSRL-1 on 13 May 2016 NAAMES flight in the Western North Atlantic Modified from Neukermans et al. (2018).

specially designed optical filters are required to spectrally separate molecular and particulate backscatter. In the transmitter, most implementations require a frequency-tunable single-mode laser transmitter, which involves injection-seeding a specially-designed pulse laser with a tunable continuous wave seed laser for precise control of the output wavelength to match the optical filters in the receiver. Concepts do exist that employ multimode laser transmitters; however, these require interferometric receiver filters that must be precisely matched to the characteristics of the laser. Perhaps due to the currently low demand for HSRL instruments and the high cost of the laser and receiver components, commercial lidar vendors have not developed HSRL instruments as a product.

Satellite

While aircraft-flown lidars have provided ocean measurements for decades (see above), the power of satellite-based lidar for ocean biology measurements has been demonstrated only recently (Behrenfeld et al., 2013, 2017; Churnside et al., 2013; Lu et al., 2014; Hostetler et al., 2018). These studies involved analysis of data from the CALIOP instrument on the CALIPSO platform which was designed for atmospheric measurements. It turned out, however, that its 532-nm channels are also sensitive to ocean backscatter. The relatively coarse vertical resolution of CALIOP (30 m in the atmosphere and 23 m in the ocean) and poor detector transient response make vertically resolved ocean retrievals impractical. However, significant scientific impacts have been realized using vertically integrated CALIOP subsurface ocean data. Behrenfeld et al. (2013) used CALIOP data to retrieve particulate backscattering coefficients (b_{bp}) for the global oceans and, employing published relationships based on b_{bp}, estimated particulate organic carbon (POC) and phytoplankton biomass, showing that the lidar retrievals were consistent with those obtained with the MODIS spaced-based radiometer.

One (of many) particular strengths of satellite lidar observations is in studying high latitude ocean regions, where ocean color observations from passive radiometers are incomplete (indeed, often completely absent) due to low solar angle and the presence of sea-ice and clouds. Supplying its own light source, CALIOP has already provided an uninterrupted record of plankton stocks for the ice-free portions of the polar oceans. Additionally, being a polar orbiting satellite, the density of retrievals near the poles is superior to that at lower latitudes. Behrenfeld et al. (2017) used a decade of monthly-resolved CALIOP data to demonstrate the processes governing the balance between phytoplankton division and loss rates, thereby advancing a new and evolving understanding of plankton blooms (Behrenfeld, 2010; Behrenfeld and Boss, 2017). An additional finding was that inter-annual anomalies in northern and southern polar-zone plankton stocks were of similar magnitude but driven by different processes. Specifically, growth and loss processes dominated inter-annual variability in the northern polar zone, while variations in plankton stocks of the southern polar zone predominately reflected changes in the extent of ice-free area.

While the atmosphere-focused CALIOP instrument provides valuable ocean data products, it has exceeded its 3-year design lifetime by over 9 years. Significant advances in science capability are envisioned for a follow-on satellite lidar optimized for ocean (as well as atmospheric) retrievals (Hostetler et al., 2018) (**Table 1**). Several advances are currently possible:

TABLE 1 | Characteristics of upper-ocean biology that can be derived from current and potential future satellite lidar missions Neukermans et al. (2018).

Upper-ocean biology characteristic	Current satellite lidar: CALIOP on CALIPSO	Future satellite lidar: ocean-optimized
Phytoplankton biomass	Surface-weighted values consistent with weighting of passive ocean color estimates	Vertically resolved profiles to~three optical depths; separate estimates of pigment absorption and CDOM (with addition of 355 nm measurements)
Phytoplankton composition and succession	Not available	Potential for crude PFT discrimination from depolarization and wavelength dependence of backscatter
Phytoplankton bloom phenology and bloom state	Biomass retrieval under conditions impossible for ocean color: high-latitude winter, night, through aerosol and optically thin clouds, between clouds in broken cloud systems, and in the proximity of ice;~monthly resolution	Same plus vertically resolved profile of phytoplankton abundance to~three optical depths
Organic carbon pool	Surface-weighted estimates of POC	Vertically resolved estimates of POC and CDOM.
Particle size distribution	Not available	Slope of particle size distribution from particle backscatter at two wavelengths at weak particle absorption wavelengths
Phytoplankton physiology	Not available	Nutrient and radiative stress from day-night comparisons of Chl-*a* fluorescence

1. *Higher vertical resolution:* Lidar signals attenuate rapidly with depth, for instance, by a factor of 400 at three optical depths, beyond which the lidar signal is generally not useable due to low signal-to-noise. At CALIOP's 532-nm wavelength, this three-optical-depth limit corresponds to about 50 m in geometric depth in the clearest waters and much less in more turbid waters, which leaves only one or two useable points in the 23-m resolution CALIOP profile. In future space-borne lidars, vertical resolutions of <3 m are achievable with current technology and would enable profiling of vertical structure in backscatter to three optical depths. Such profiling would represent a significant advantage over passive radiometric measurements, for which the measured signals are weighted exponentially toward the ocean surface (with 92% of the signal coming from the first optical depth). Vertically resolved lidar data of phytoplankton biomass, for instance, will reduce errors in estimates of net primary productivity that result from using surface-weighted retrievals to represent ocean properties at greater depths (Platt and Sathyendranath, 1988; Zhai et al., 2012; Hill et al., 2013; Schulien et al., 2017).
2. *Higher spatiotemporal resolution:* In polar regions, CALIOP or future lidar missions may be used to better document the marginal ice zone composed of a mixture of sea ice and open waters, as well as the frequent open-water fractures found in the ice pack, where phytoplankton growth may be significant and has been hard to capture (see **Figure 4**). In particular, observations in the leads may be exploited to investigate under-ice phytoplankton dynamics, one of the mysteries of

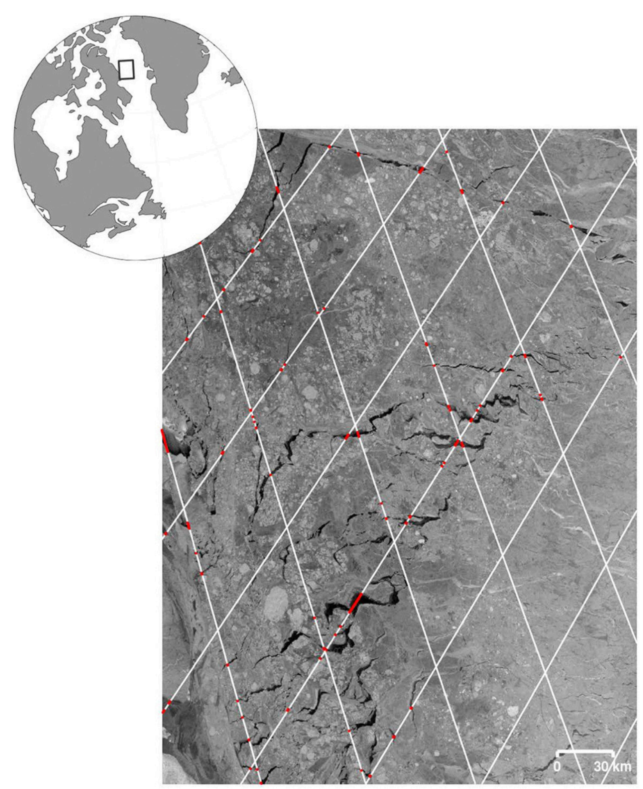

FIGURE 4 | Sentinel 1 SAR (Synthetic Aperture Radar) image on 10th April 2017 in the Baffin Bay (pixel size: 100 × 100 m), showing open-water fractures (black pixels) in the ice pack. White lines depict CALIOP tracks over a 16-day orbit repeat cycle. Red dots indicate where the lidar shots (∼100 m footprint; 330 m pulse-to-pulse along-track distance) targeted open-water areas. These represent about 3% of the total shots shown on this image.

polar environments. Major recommendations in order to achieve this goal would be to increase the spatiotemporal coverage of future lidar missions. This implies reducing footprint diameter and distance between footprints.

3. *Independent retrieval of attenuation and backscattering:* The standard elastic backscatter lidar technique used for CALIOP cannot separate the backscattered signal from attenuation, so b_{bp} retrievals in previous publications required either assuming a predictable relationship between backscatter and attenuation or combining CALIOP and passive ocean color data. The former assumptions can introduce significant errors when applied at the local scale. By adding one or more additional channels in the lidar receiver to resolve the optical signal spectrally, the existing HSRL technique enables independent and accurate retrieval of particulate backscatter and attenuation coefficients. The HSRL technique has been used for decades for aerosol measurements (Shipley et al., 1983; Piironen and Eloranta, 1994; Esselborn et al., 2008; Hair et al., 2008), and more recently to retrieve ocean particulate backscatter and the diffuse attenuation coefficient (Hair et al., 2016; Schulien et al., 2017).
4. *Addition of other backscattering wavelengths:* A future space-borne 532 nm HSRL with high-vertical-resolution capability would enable vertically resolved estimates of phytoplankton biomass, POC, and net primary productivity. Adding HSRL capability at 355 nm in addition to that at 532 would allow independent estimates of algal and CDOM absorption and information on the slope of the particle size distribution.
5. *Addition of detectors to measure fluorescence emissions:* A further promising direction for application of space-borne lidar is the retrieval of the fluorescence signature of Chl-*a* and CDOM, which would allow studies of phytoplankton physiology and a better separation of particulate and dissolved pools of organic carbon in the upper ocean. Laser-excited fluorescence from both Chl-*a* and dissolved organic matter have already been shown to be measurable by airborne lidar instruments in both coastal and open-sea waters (Hoge et al., 1993). Additionally, the ratio of chlorophyll fluorescence and backscattering has been recently found to provide important constraints for the retrieval of phytoplankton functional types (PFT) dominating upper ocean communities. With such data, studies have documented PFT changes through the evolution of the North Atlantic bloom (Cetinić et al., 2015; Lacour et al., 2017).
6. *Joint retrievals from combined passive and active sensing:* The increase in information obtained with a lidar when combined with that from passive radiometry (with the possibility of polarimetry, e.g., Stamnes et al., 2018b; see section Polarimetry Technique) has been shown to improve estimates of atmospheric aerosols and, consequently, to enhance ocean geophysical retrievals (i.e., through improved atmospheric corrections).

It follows from the above that satellite lidar observations are a natural complement to passive radiometric remote sensing. While lidar systems lack the swath width of space-based passive radiometers, the lidar has many sampling capabilities beyond those of passive ocean color. These lidar advantages include (1) measurements independent of solar angle and both day and night, enabling sensing during all seasons at high latitudes and documentation of diel plankton cycles, (2) an ocean-optimized HSRL can provide measurements through aerosol layers of any type (absorbing, as well as non-absorbing) and through optically thin clouds, (3) a lidar's small footprint (e.g., 90 m for CALIOP) enables measurements in gaps between clouds, regardless of cloud shadowing or adjacency effects that can contaminate passive retrievals, as well as sampling through small gaps within and near ice (for CALIOP, the annual coverage is comparable to MODIS at high latitudes, despite its small footprint), and (4) a future lidar with high vertical and spatiotemporal resolution capability would enable the first global three-dimensional view of global ocean plankton ecosystems in conjunction with BGC Argo floats (Johnson and Claustre, 2016).

POLARIMETRY TECHNIQUE

Measurement Principle

The overarching goal here is to determine the polarization of light scattered by suspended particles present in either the atmosphere or ocean, as a function of wavelength and scattering angle in order to derive optical properties and infer microphysical information about those particles. Due to the transverse nature of light, a plane electromagnetic wave of light can be modeled as $\mathbf{E}=\mathbf{E_0}e^{i(\mathbf{k}\bullet\mathbf{r}-\omega t)}$, where $\mathbf{E}_0$ is the complex electric field that propagates along a unit vector $\mathbf{k}$. This propagation direction uniquely determines the meridional plane for a beam of light when combined with the local vertical direction $\mathbf{z}$. The electric field $\mathbf{E}_0$ of the incident light can then be decomposed into parallel ($E_0^{||}$) and perpendicular ($E_0^{\perp}$) components with respect to this meridional plane, such that $\mathbf{E}_0 = E_0^{||} + E_0^{\perp}$. For a monochromatic energy flux, it is possible to define the 4×1 Stokes column vector $I \equiv \{I, Q, U, V\}$ using linear combinations of these complex electrical field components as follows:

$$\mathbf{I}=\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}=c\begin{bmatrix} E^{||}E^{||*}+E^{\perp}E^{\perp*} \\ E^{||}E^{||*}-E^{\perp}E^{\perp*} \\ E^{||}E^{\perp*}+E^{\perp}E^{||*} \\ i(E^{||}E^{\perp*}-E^{\perp}E^{||*}) \end{bmatrix} \quad (3)$$

where c is proportional to the electric permittivity and the magnetic permeability of the medium. The Degree of Polarization can then be defined as: $DoP = \frac{\sqrt{Q^2+U^2+V^2}}{I}$, which spans from 0 when the light is completely unpolarized to 1 when the light is fully polarized. When the circular polarization component, V, is neglected, then the Degree of Linear Polarization is $DoLP = \frac{\sqrt{I^2+U^2}}{I}$. A polarimeter provides Stokes parameters I, Q, U and V by separating and modifying the orthogonal polarized intensities $E^{||}E^{||*}$ and $E^{||\perp}E^{\perp*}$ of the measured light. The separation and modification can be achieved by passing the light through a polarizing filter and retarder before measurement. It is worth to note that the V component is typically very small at TOA/in the atmosphere and is not measured (or at least not reported) by most polarimeter instruments. The general measurement concept is described by the following equation (Chandrasekhar, 1960; Hansen and Travis, 1974):

$$I_m(\chi, \varepsilon) = \frac{1}{2}\left[I_i + Q_i \cos 2\chi + (U_i \cos \varepsilon - V_i \sin \varepsilon) \sin 2\chi\right] \quad (4)$$

where subscript i indicates the Stokes vector elements of the incident light while m indicates the intensity of the measured light, χ is the rotation angle between polarizer axis and the parallel electric field direction and ε is a constant retardation difference between the parallel and perpendicular electrical fields. Thus, the I, Q, and U components can be measured by recording intensities of the measured light with three different orientations of polarizers.

Single Scattering Properties

The Stokes vector defines the polarization state of the incident and measured light. The Mueller matrix is a 4 × 4 transformation matrix describing the scattering process and relating the incident light to the observed light as a function of scattering angle. Thus, the Mueller matrix depends on the properties of the scattering object (i.e., aerosols, hydrosols, or surface). In remote sensing of aerosols and hydrosols, the Mueller matrix is obtained through light scattering theory based on the far-field approximation. Mie scattering refers to light scattering by homogenous spherical particles with a specific complex refractive index and size distribution with particle radii of specific range, which is often used to approximate particle scattering in turbid media. When particles are much smaller in size than the wavelength of incident light, the Mueller matrix can be approximated by the Rayleigh theory of scattering. The scattering by air molecules follows the Rayleigh scattering theory supplemented with a specific depolarization ratio to account for the molecules anisotropy (i.e., molecules do not behave as perfect dipoles) while pure water follows the Einstein-Smoluchowski-Cabannes fluctuation theory of light scattering (Litan, 1968). Also, several numerical approaches have been developed to calculate properties of single scattering of light by larger particles of arbitrary shape and composition such as the T-matrix, Finite Difference Time Domain and Discrete Dipole Approximation (Waterman, 1971; Purcell and Pennypacker, 1973; Yang and Liou, 1996; Mishchenko and Travis, 1998; Yurkin and Hoekstra, 2007). Additionally, inhomogeneous spherical particles can well approximate the backscattering of phytoplankton particles (Robertson-Lain et al., 2014; Moutier et al., 2017; Poulin et al., 2018). In the ocean, due to a lack of knowledge of the shape and composition of hydrosols, spherical particles are typically assumed for RT studies given a refractive index and Junge (power-law) slope for the size distribution. Hydrosol particulates can be separated into organic (phytoplankton) and in-organic (non-algal particles, NAP). Organic particles have a low refractive index relative to the water ($\boldsymbol{n_{ph}} = 1.02\sim1.08$) due to the high water content, while NAPs are more refracting ($\boldsymbol{n_{nap}} = 1.1\sim1.22$) (Aas, 1996; Stramski et al., 2004). The apparent optical effect (i.e., the bulk or mixed Mueller or scattering matrix) is calculated as the relative contribution in scattering of each component. **Figure 5** shows the 4 independent elements of the scattering matrix computed from Mie theory for phytoplankton (blue curve) and NAP (red curve), and for mixtures (black curve) based on their scattering coefficient as a weighted average.

Figure 5 shows the phase function and the normalized polarization components of the Mie scattering elements (F_{11}, F_{12}/F_{11}, F_{33}/F_{11}, and F_{34}/F_{11}) for one case of chlorophyll and NAP concentrations and for one case of Junge Particle Size Distribution (PSD) slope ($\boldsymbol{\xi_{nap}} = \boldsymbol{\xi_{ph}} = 4$), as an illustration. The matrix is calculated for spherical particles. The polarization elements (F_{12}/F_{11}, F_{33}/F_{11}, and F_{34}/F_{11}) of the scattering matrix of phytoplankton particles are similar to those obtained for Rayleigh scattering, because the relative refractive index is very low, i.e., 1.06, similar to what was presented in **Figure 4** of Gilerson et al. (2013). In contrast, the shape of the polarized scattering matrix elements of NAPs are significantly different, due to their high refractive index, with exception of the near forward and backward direction where it exhibits a weak polarization effect according to Mie-Lorenz theory. The figure shows the strong separability of the two types of particles when using the polarized components of the scattering matrix, as opposed to the F_{11} element only.

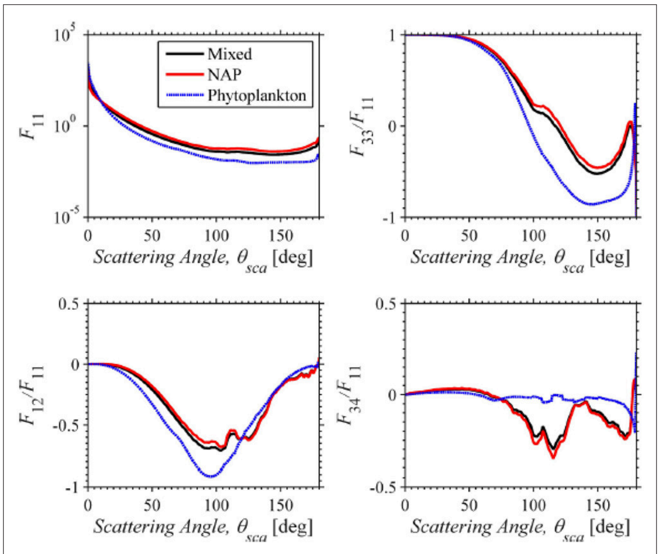

FIGURE 5 | Scattering phase function and normalized polarization elements of the scattering matrix from Mie calculations for one case as an illustration for $n_{nap} = 1.18$, $n_{ph} = 1.06$, $\xi_{nap} = 4.0$, $\xi_{ph} = 4.0$, [NAP] = 1.45 g m^{-3}, and [Chl] = 10.5 mg m^{-3} at 440 nm. Reuse with permission from Ibrahim et al. (2012).

The Utility of Polarimetry in Ocean Remote Sensing

Inherent Optical Properties

Beam attenuation coefficient

The particulate attenuation coefficient, c_p, of hydrosols co-varies with the particulate organic carbon concentration (POC) as well as with the phytoplankton carbon biomass (Loisel and Morel, 1998; Behrenfeld and Boss, 2003; Behrenfeld et al., 2005; Cetinić et al., 2012; Graff et al., 2015; Werdell et al., 2018). Several studies suggest that there is a first-order relationship between the ratio of c_p to chlorophyll concentration (c_p:Chl), which may be used as an index of phytoplankton carbon (C) biomass to chlorophyll concentration ratio (C:Chl) and phytoplankton physiology, which is important for estimating primary production of the oceans. Thus, retrieval of the attenuation coefficient from remote sensing would allow for a drastically better understanding of the carbon cycle on the global scale, which is a primary goal of many ocean color satellite missions.

Ibrahim et al. (2012, 2016) have shown that there is a direct relationship between the attenuation to absorption ratio and the Degree of Linear Polarization (DoLP; which is given by setting $V = 0$ in the definition of DoP) just beneath the ocean surface at three wavelengths in the visible and for a wide range of viewing geometries. The relationship shown in top row of **Figure 6** is based on VRT simulations for a large dynamic range of coastal water IOPs (Ibrahim et al., 2016). This relationship was confirmed with in-water observations showing the possibility of retrieving the attenuation coefficient of hydrosols as shown in the lower row of **Figure 6**. These results are also consistent with the theoretical analysis of Chami and Defoin Platel (2007) based on RT modeling. In addition, Tonizzo et al. (2009) also illustrated the sensitivity of DoLP to variations in water types. Based on in-water observations, clear waters show high DoLP values in the blue and green wavelengths, while the opposite occurs for the more productive water. Adding CDOM in the more turbid water increases the DoLP in the blue even more, due to the decreased number of scattering events.

Particle sizes and complex refractive index

Oceanic hydrosols such as plankton and mineral particles vary in size and composition. Traditionally, the PSD is retrieved from the spectral slope of the backscattering coefficient, which can be derived from spaceborne radiometers by assuming the power law (Junge) size distribution for spherical particles (Loisel et al., 2006; Kostadinov et al., 2009). Laser diffraction measurements of the particle size distribution in different oceanic regions showed that the size distribution of marine particles can be approximated by the Junge-like power law except in cases where there is are rapid changes in a phytoplankton species population (Buonassissi and Dierssen, 2010; Reynolds et al., 2010, 2016).

Organic particles have low refractive index and thus are less effective scatterers, while inorganic hydrosols such as sediments have a high refractive index, implying that they are more efficient scatters that tend to depolarize the light. In coastal waters, the DoLP is generally smaller than in the open ocean due to the high amount of sediments with a high bulk refractive index.

In **Figure 7**, Loisel et al. (2008) showed DoLP for various scattering angles for low and high refractive index particles. The molecular scattering exhibits very strong polarization at 90° scattering angle, decreasing when moving to smaller/larger angles. When particles are added, the position of the peak of polarization, as well as its intensity, changes on particle size, refractive index, and concentration. For large particles, the DoLP decreases strongly. For this reason, the measurement of DoLP provides information on the relative proportion between small and large particle sizes in the observed field. Multiple scattering and scattering by non-spherical particles also tend to lower the DoLP (Ivanoff et al., 1961). Tonizzo et al. (2011) have shown retrievals of hydrosols microphysical properties using a recursive fitting of the *in-situ* DoLP measurements with RT simulations. For remote sensing applications, Ibrahim et al. (2016) suggested to estimate the bulk refractive index using the CDOM corrected spectral attenuation coefficient to approximate the Junge PSD, derive the backscattering ratio from the backscattering and total scattering coefficient and apply the method of Twardowski et al. (2001) based on the Mie theory.

Improved net-primary productivity (Npp)

In complex waters, the separation between the optical contributions of different ocean constituents becomes more challenging. The ambiguity in the inverse problem using scalar radiance is too high. Thus, the estimate of primary productivity can be biased in these water conditions. Polarimetry potentially allows the separation of organic and in-organic contributions, which in-turn allows improved NPP estimates. Chami and McKee (2007) suggest that it is possible to retrieve the suspended particulate matter (SPM) from DoLP measurements at the Brewster angle. Using theoretical modeling they showed that

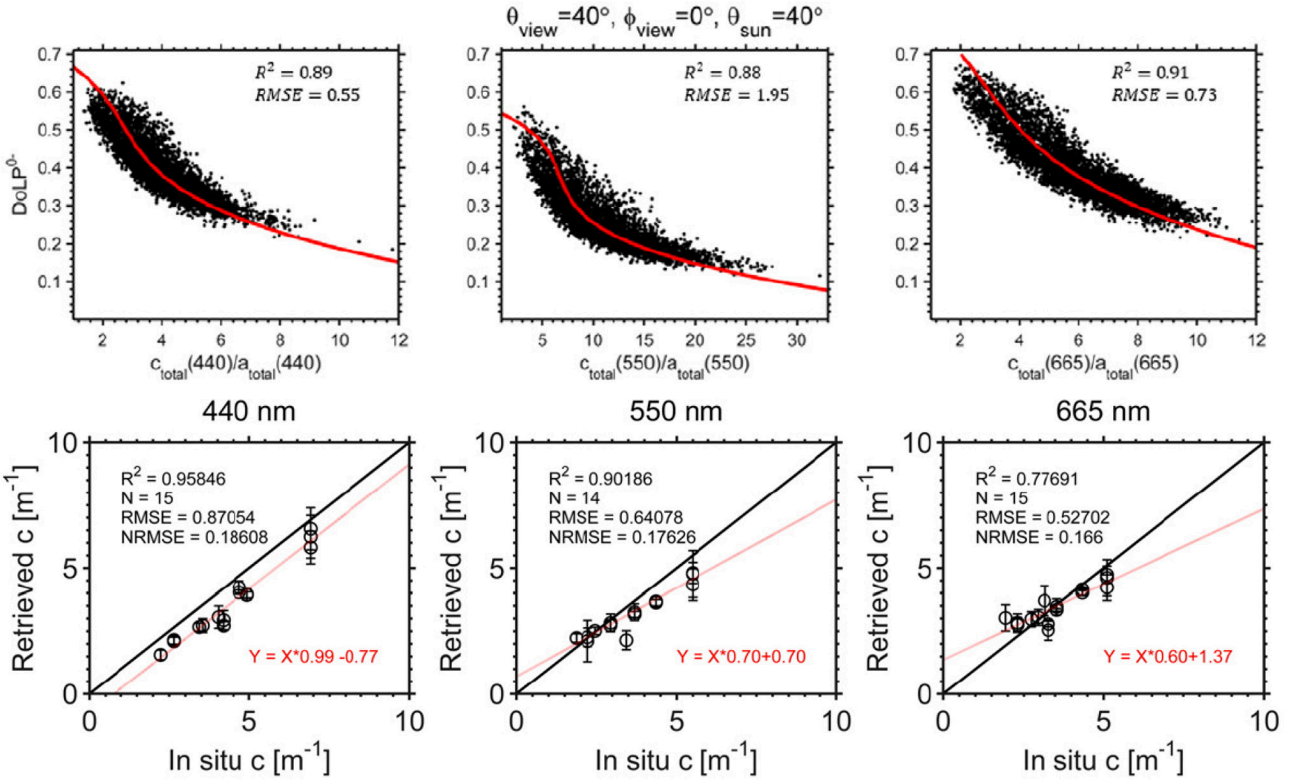

FIGURE 6 | The upper row shows the simulated DoLP just beneath the ocean surface vs. the ratio of the attenuation to absorption coefficients for three wavelengths in the visible wavelengths at one specific geometry and for a wide range of coastal ocean IOPs. The lower row is the validation based on in-water polarimeter observations and in-water beam attenuation coefficient measurements from WETLabs ac-s. Reuse with permission from Ibrahim et al. (2016).

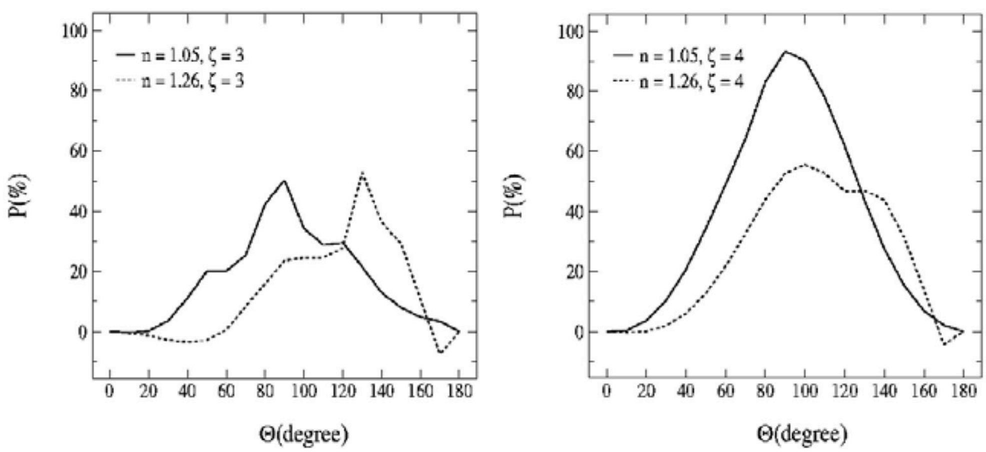

FIGURE 7 | The DoLP (%) [labeled as P(%)] in-water as a function of scattering angle for four different polydisperse assemblages of hydrosols: size distributions with the Junge PSD slope $\xi = 3$ **(left)** and $\xi = 4$ **(right)** and particles with low refractive index (organic particles $n = 1.05$) and high refractive index (in-organic particles $n = 1.26$). Reuse with permission from Loisel et al. (2008).

an empirically based inversion approach could retrieve the concentration of inorganic particles from underwater polarized radiance measurements regardless of the phytoplankton content in coastal waters.

Turbidity

Chami et al. (2001) and Chami and McKee (2007) have shown that it is possible to retrieve the turbidity in complex waters using the polarized reflectance through a RT sensitivity analysis. It is possible to discriminate the sediment concentration from the phytoplankton using the polarized signal at the red wavelength. The polarized reflectance shows an enhanced sensitivity to in-water sediments and their microphysical properties, as compared to the remote sensing reflectance (Rrs). Chami and McKee (2007) showed the potential of the degree of polarization measurements at the Brewster angle in the specular direction to retrieve the concentration of sediment particles. Ibrahim et al. (2016) corroborated some of these results in a recent study.

Enhanced Atmospheric Correction

Improved aerosol characterization

Improved aerosol characterization will improve atmospheric correction and thus directly benefit ocean color remote sensing. There is a strong heritage within the atmospheric community of using multi-angular polarimeters for aerosol characterization, beginning with POLDER (Deuzé et al., 2000; Hasekamp and Landgraf, 2005; Dubovik et al., 2011; Hasekamp et al., 2011, 2019; Tanré et al., 2011). This heritage and further studies have shown that multi-angle polarimetry advances aerosol characterization beyond the capabilities that single-view total radiation measurements can achieve in terms of number of microphysical characteristics retrieved (Chowdhary et al., 2001, 2002, 2005; Waquet et al., 2009, 2013; Harmel and Chami, 2011; Knobelspiesse et al., 2012; Ottaviani et al., 2013; Peers et al., 2015; Xu et al., 2016, 2017; Gao et al., 2018; Stamnes et al., 2018a).

Improved glint correction

He et al. (2014) provide evidence of the advantages of including polarimetry for atmospheric correction over the ocean. They describe a method for retrieving the normalized water-leaving radiance (L_{wn}), using the parallel polarized radiance (PPR $=$ $I + Q$), where I and Q are the first two components of the Stokes vector **I**. Their results, both from simulations and from application to POLDER data, demonstrate that use of PPR provides two important enhancements to ocean color retrieval. First, it reduces the sun glint at moderate to high solar zenith angles. Second, it boosts the ocean color signal relative to the total radiance received by satellite sensors at large view zenith angles. These advantages are explained by the compensating effect between the total radiance and the polarization. For example, as the view zenith angle increases, because of the longer path length through the atmosphere, the total radiance received by the satellite increases, causing the relative ocean color signal reaching the satellite to decrease. Meanwhile, the magnitude of Q increases with path length, but in the negative sense, which offsets the increase in I, and slows down the increase in PPR with path length through the atmosphere. Harmel and Chami (2013) have also shown that a better characterization of the glint signal is obtained using multi-angular polarimetric measurements from the PARASOL sensor. One may also consider using unpolarized reflectance instead of total reflectance to retrieve water properties, as suggested by Frouin et al. (1994) and Krotkov et al. (1992). The contribution of the water body to the TOA signal is generally enhanced using this component, except over optically thick atmospheres (due to multiple scattering), making the atmospheric correction easier. Sun glint using this method is mitigated and using polarization information in addition to spectral information in the near infrared and shortwave infrared facilitates determination of the aerosol model necessary for the atmospheric correction (Foster and Gilerson, 2016).

Turbid water atmospheric correction

Zhai et al. (2017) showed that in scattering coastal waters, the polarized reflectance at the TOA in the NIR bands is less significant than the scalar radiance, thus enabling improved separation of aerosol and ocean contributions to the observed signal. The growing interest in IOPs in the UV poses a new challenge for atmospheric correction because of the confounding effects of absorption by aerosols, and specifically lofted smoke or dust layers. Collocated lidar and polarimetry can help to unravel the in-water and in-air contributions but, if not available, emerging passive techniques based on spectral and/or multi-angle observations in the O_2 A-band ($\sim$765 nm) can be used (Davis and Kalashnikova, 2018, and references therein).

Simultaneous retrieval of aerosol and water-leaving radiance

Several simultaneous retrieval algorithms have been developed using multi-angle polarization measurements, where the aerosol properties and the water-leaving radiance are retrieved simultaneously. Chowdhary et al. (2005) developed a joint retrieval algorithm using the RSP data that retrieved the aerosol properties and water optical properties with a bio-optical model parameterized by chlorophyll concentration. Hasekamp et al. (2011) developed a retrieval algorithm using measurements from PARASOL with a bimodal aerosol model and an ocean model parameterized by chlorophyll concentration, wind speed and direction, and foam coverage. Xu et al. (2016) developed a retrieval algorithm using the AirMSPI dataset with a multi-pixel smoothing constraint and a simplified bio-optical model. Gao et al. (2018) developed a simultaneous retrieval algorithm for coastal waters using a bio-optical model including contributions from phytoplankton, CDOM, and non-algal particles. Stamnes et al. (2018b) developed a retrieval framework that can combine lidar and polarimeter measurements (HSRL+RSP) in the coupled atmosphere-ocean system to simultaneously retrieve the aerosol microphysical and ocean properties.

Challenges in Polarimetric Ocean Remote Sensing

Vector Radiative Transfer Models

Bio-optical model

Traditionally, the ocean color community has relied mostly on scalar radiative transfer codes such as Hydrolight for remote sensing purposes (Mobley, 1994). However, Hydrolight lacks the ability to simulate a polarized light field in the ocean, and therefore cannot support the development of new remote sensing methods that will make use of polarization measurements. VRT codes that do simulate the polarized field require better representation of aerosol and hydrosol optical properties, including incorporation of the full 4×4 single scattering matrix of particle properties into the VRT code. It is therefore necessary in order to have a physically consistent scattering matrix to specify the PSD, complex refractive index, and shape and apply one of several single scattering methods such as Mie (spherical), T-matrix (elliptical), Discrete Dipole Approximation, or geometric optics to calculate the scattering matrix. In terms of hydrosols, there is a significant lack of observational information to constrain particle characteristics, especially morphology, in order to specify particle microphysical properties and calculate the intrinsic particle scattering properties. The specification of particle properties therefore introduces uncertainty into VRT attempts to simulate the polarized light field. Additionally, a full coupling between single scattering properties and bulk IOPs is necessary, and yet are not mapped out.

Fully coupled AO RT models

The ultimate goal of ocean color (scalar and/or polarimetric) measurements is to obtain information about the "health" of its biogenic constituents. For this purpose, access to accurate RT models of the coupled AO system is of paramount importance. To interpret polarimetric measurements, reliable, accurate, and efficient modeling of the polarized radiation represented by the Stokes vector in open oceanic regions as well as turbid coastal areas is required. For example, as reviewed by Stamnes et al. (2018a), such modeling is needed to develop forward-inverse methods required to quantify types and concentrations of aerosol and cloud particles in the atmosphere, as well as dissolved organic and particulate biogeochemical matter in lakes, rivers, coastal and open-ocean water, and to simulate the performance of remote sensing detectors deployed in space. For example, machine learning techniques for accurate cloud screening and retrieval of aerosol and water IOPs in complex AO systems can be based on extensive RT simulations of the coupled AO system (Fan et al., 2017; Chen et al., 2018). Polarized VRT simulations of the coupled AO system can also be used in conjunction with inverse modeling to retrieve the IOPs and vertical location of absorbing atmospheric aerosols as discussed by Stamnes et al. (2018a). Coupled VRT simulations are also required for accurate simultaneous retrieval of aerosol and ocean properties using polarimeter data (Xu et al., 2016; Stamnes et al., 2018b). Such models exist and employ various methods to solve the RT equation, for example adding and doubling (de Haan et al., 1987; Chowdhary et al., 2006; Xu et al., 2016), successive-order-of-scattering (Zhai et al., 2010; Chami et al., 2015), matrix operator (Ota et al., 2010), and Monte Carlo (Ramon et al., 2019). Research frontiers on RT modeling in coupled ocean-atmosphere systems are discussed in great details in Chowdhary et al. (2019). For applications at high latitudes, the curvature of the Earth should be accounted for in the RT simulations (Ding and Gordon, 1995; He et al., 2018), and for analysis of airborne polarimeter data coupled RT simulations are also required (Xu et al., 2016; Stamnes et al., 2018b).

In-elastic scattering VRT

Inelastic scattering in ocean waters includes Raman scattering, Fluorescence by Colored Dissolved Organic Matter (FDOM), and fluorescence by phytoplankton as a by-product of photosynthesis. Scalar solutions of the radiation field have been published with the capability of modeling these effects (Mobley, 1994; Schroeder et al., 2003). In this new era of remote sensing using polarized signals, it is important to have an accurate radiative transfer model that can couple the effect of polarization, flexible atmosphere, and ocean optical properties, and both elastic and inelastic scattering effects. Zhai et al. (2017) have developed a vector radiative transfer model that uniquely combines all these features. Later Zhai et al. (2018) further incorporated photochemical and non-photochemical quenching effects in the solution, which can model fluorescence quantum yield as a function of photosynthetic available radiation. This new radiative transfer package will be an important tool for exploring information content in hyperspectral and polarimetric measurements of ocean constituents.

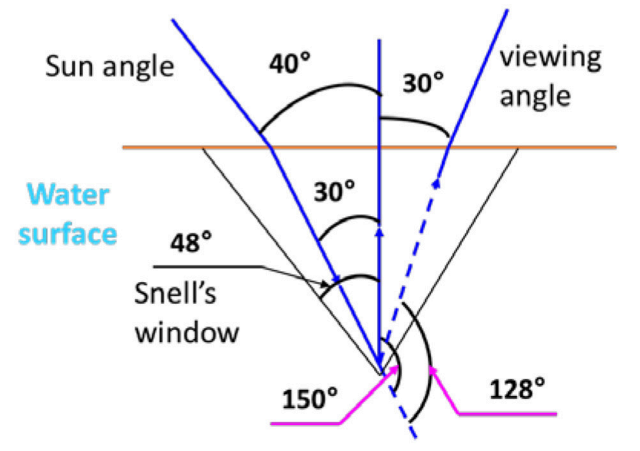

FIGURE 8 | Air-sea interface showing the refraction of the light from below to above the ocean. The solid black lines show the limits of the Snell window.

Multi-angular limitation

Snell's cone due to surface refraction limits the angular information from beneath the ocean surface as shown in **Figure 8**. A large range of the angular information below the surface is not transmitted to above the surface due to the total internal reflection. Thus, the application of algorithms that utilize the angular distribution of ocean upwelling light, could be limited, however further analysis is required.

Instrumentation

Characterize hydrosol scattering matrix, size distribution, and refractive index

So far there are very few measurements of the microphysical properties of hydrosols such as the refractive index and the scattering matrix. Voss and Fry (1984) attempted to measure the scattering matrix of hydrosols in the open ocean. Their measured scattering matrix in clear water conditions showed that the elements of the scattering matrix does not follow the Rayleigh scattering pattern, although there are similarities. All the off-diagonal elements, except F_{12} and F_{21} are zeros due to a slight particle anisotropy of orientation preference. Their conclusion is that Mie scattering cannot reproduce the measured scattering matrix due to the limitations of sphericity assumption. Volten

TABLE 2 | List of *in-situ* polarimeters for ocean applications.

Instrument	Spectral range	Viewing angles	Deployment	References
CCNY Polarimeter	Hyperspectral (350–800 nm)	Hyperangular	In-water	Tonizzo et al., 2009
CCNY HyperSAS-POL	Hyperspectral (350–800 nm)	Single View angle	Continuous Ship-borne or platform	Harmel et al., 2011; Ottaviani et al., 2018
POLRADS	410, 436, 486, 526, 548, and 616 nm	Hemispheric geometry	In-water	Voss and Souaidia, 2010
NRL-DC Polarimeter	Hyperspectral (380–950 nm)	Single View angle	Ship-borne (above-water)	

TABLE 3 | List of Multi-angular airborne polarimeters that can be used to develop and test algorithms.

Instrument	Spectral range*	Viewing angles	DoLP accuracy	Reference
RSP	410, 470, 555, 670, 865, 960, 1,590, 1,880, 2,250 nm	Hyperangular (155 angles)	0.0015 to 0.002	NASA GISS, Brian Cairns (Chowdhary et al., 2001)
Air-HARP	440, 550, 670, 870 nm	20 angles for 440, 550, 870 nm bands and 60 for 670 nm	<0.01	UMBC Vanderlei Martins
SPEX-Airborne	400–800 nm (2 nm radiance, 15–45 nm DoLP)	(+/−56°, +/−42°, +/−28°, +/−14°, 0°)	<0.002+0.005*DoLP	SRON Otto Hasekamp (Snik et al., 2010)
AirMSPI	*355, 380,* 445, 470, 555, 660, 865, and *935* nm	Variable, gimbaled system	0.003 to 0.01	JPL David Diner (Diner et al., 2013)
Versatile Imager for Coastal Ocean (VICO)	435, 550, 625, and 750 nm	Variable, gimbaled system (+/− 65°)	<0.0025	NRL-DC, (Bowles et al., 2015)

Italic font indicates channels without polarimetric sensitivity.

et al. (1998) realized laboratory measurements of F_{11} and F_{12} for phytoplankton cultures signifying that Mie scattering cannot approximate scattering by phytoplankton particles. Follow-up *in-situ* measurements of the scattering matrix in clear waters, and for different types of turbid waters including sediment-laden and phytoplankton dominated waters, will be critically relevant to assessing and improving retrievals using polarimeter and hyperspectral remote sensors, such as NASA's PACE mission. And, measurements of the phase function near or at 180 degrees will be important for improving understanding of current and future lidar ocean measurements. Current *in-situ* commercial instruments, such as the WETLabs MASCOT and LISST-VSF, which measures F_{11} and F_{12} of the scattering matrix, will provide additional insight into the hydrosol microphysical properties in conjunction with PSD instruments such as the Sequoia Scientific LISST (Karp-Boss et al., 2007; Sullivan and Twardowski, 2009; You et al., 2011; Gilerson et al., 2013).

In-situ polarimetric instruments

Table 2 shows potential *in-situ* polarimetric instruments that can be deployed either in- or just above-water which can be used to develop and validate algorithms:

Airborne polarimeters

Airborne polarimeters have been used for numerous field campaigns aimed at studying aerosols and clouds. Some of these instruments could be used to develop remote sensing algorithms for IOP retrievals. **Table 3** provides some of these instruments.

Previous, Current, and Future Missions

Previous and current ocean color missions sponsored by various space agencies (see illustrative example in **Figure 9**) have focused on utilizing the spectral information at one viewing geometry. Examples include SeaWiFS, MODIS-Aqua/Terra, SNPP-VIIRS, MERIS, Sentinel-3, and GOCI. Multi-angle satellite instruments such as MISR-Terra have been used extensively for aerosol characterization by utilizing the angular distribution of scattered light to distinguish the aerosol properties, however the instrument only measures total (intensity) scattered radiation and is missing the polarization signal. JAXA's SGLI onboard GCOM-C is a single-view instrument that measures the polarized light at two spectral channels in the red and NIR wavelengths. Multi-angle polarimetric information, however, is crucial for retrieving properties about the Atmospheric-Oceanic (AO) system. While there may be some limited capability for SGLI's polarized channels for retrieving ocean properties, SGLI is expected to help quantify the surface glint contribution, which is highly polarizing.

Space-borne multi-angle polarimeters such as CNES POLDER/PARASOL have been successful in characterizing aerosol and cloud optical and microphysical properties. There are very few studies examining the utility of POLDER/PARASOL for ocean remote sensing applications. In fact, only one study by Loisel et al. (2008) has shown the potential of using the DoLP to distinguish hydrosols' microphysical properties from POLDER. In **Figure 10**, the radiative transfer simulations, performed for different polydisperse assemblages of suspended marine particles showed that there is an hyperbolic trend between R_{rs} and the DoLP. The scatter of the POLDER data observed around the hyperbolic trend may be explained by changes in the bulk particulate assemblage.

In the next few years we expect the launch of new space-borne polarimeters. NASA's PACE mission will host two advanced polarimeters, HARP2 and SPEXone. HARP2 is a hyperangular

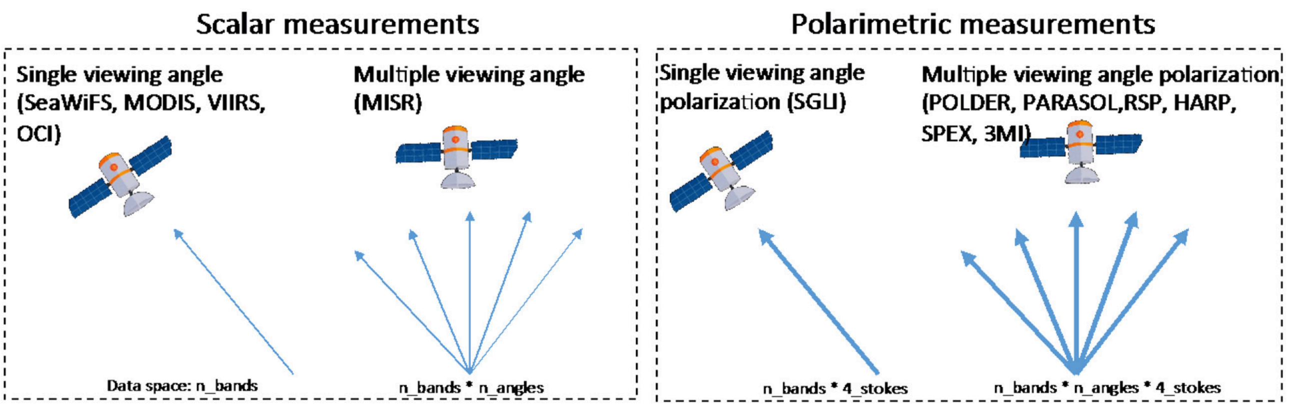

FIGURE 9 | Observing system configurations of scalar and polarimetric measurements at single and multiple viewing geometries. The data space indicates the increased dimension of multi-angular polarimeters from single view radiometers as a proxy to the information content of the measurements.

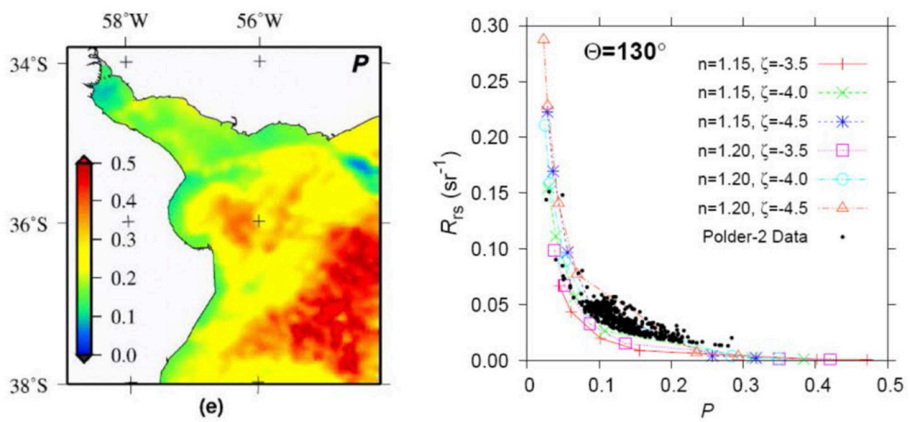

FIGURE 10 | POLDER retrieval of the DoLP shown in the left-hand side figure over complex coastal waters (Rio de la Plata estuary). The right-hand side shows the relationship, obtained from radiative transfer simulations, between the DoLP (shown as "P" on the x-axis) and the R_{rs} for different hydrosol microphysical properties. The black dots show observed data points overlaid the theoretical relationship. Reuse with permission from Loisel et al. (2008).

polarimeters that measures light at 3 visible and 1 NIR channel. The instrument is designed for cloud remote sensing and is expected to significantly benefit aerosol remote sensing. SPEXone is a hyperspectral polarimeter that monitors the spectral range 385–770 nm continuously (resolution 2–5 nm for radiance and 15–40 for DoLP) at five viewing angles. The instrument is designed specifically for aerosol remote sensing (Hasekamp et al., 2019). Another NASA mission expected in the same time frame as PACE is MAIA, which will include a multiangle polarimeter with nadir spatial resolution of 200 m and the ability to point at specific targets. However, MAIA's science objectives are public health, and therefore will be targeting land-based population centers and will not obtain global coverage. In addition to the new NASA missions, ESA is planning to launch 3MI which is a follow-on instrument of POLDER, but with added spectral capability that will enhance its ability to characterize aerosol and cloud properties (Fougnie et al., 2018). While these planned sensors will aid ocean color retrievals indirectly by better characterizing aerosols and improving atmospheric correction, none of these sensors are designed for direct ocean color applications for the following reasons:

1) Coarse spatial resolution (3–4 km).
2) Non-pointing instruments, which leads to measurements in viewing plane that could be contaminated by glint. Aerosol and cloud polarimetry prefer principal plane measurements to maximize the range of scattering angles, however ocean polarimetry needs to measure the light at an off-principal viewing plane to reduce glint, while still being not be too far from the principal plane in order to maximize the polarized signal (i.e., azimuth angle = 30 to 60°). This preference means that ocean coverage would be reduced.

For ocean applications, the radiometric accuracy of the instrument should be very high to enable the detection of small-scale variations of the polarized light in the ocean. For example, Ottaviani et al. (2018) have shown that based on RT simulations, it is possible to detect the polarized ocean reflectance using sensors better than 8.5×10^{-4} in polarimetric accuracy. Detecting variability in DoP due to changes in the IOPs from space observations is more attainable than the polarized reflectance due to the fact that DoP is a ratio that primarily depends on the random noise of the detector. Meanwhile the polarized reflectance is more sensitive to the systematic uncertainty of the sensor that can be more significant than the random noise term, however it depends on the instrument design. Although, there are no studies on the requirements of ocean polarimeters, in-terms of detection uncertainties, SPEXone on-board the planned PACE mission is expected to be utilized for ocean applications due to its high polarimetric accuracy (see **Table 3**), however limited in the spatial resolution. State of the art sensors, with improved polarization detection capability designed for ocean color applications are needed.

OUTREACH AND EDUCATION

The aim of this section is to provide some suggestions to better connect scientist with end-users in the domain of polarimetry and lidar technologies. End-users include peers, not necessarily in the same field of work, funding organizations, decision makers, and the general public. All of them have a role to play in planning and implementing ocean observation and monitoring. Polarimetry and lidar technologies have a great potential in filling gaps in societal and scientific knowledge needs. But improvements in technologies access, data management, accessibility and dissemination are clearly needed.

No *in-situ* or airborne oceanic profiling lidar are currently commercially available. The current oceanic profiling lidar are developed in laboratories. For most laboratories, the task of developing their own *in-situ* or airborne lidar is intensively labor and cost consuming that will prevent short-term efforts for the dissemination of these instruments. This can only be done in conjunction with small and medium enterprises (SMEs). Because of the size of the market, public funding will be necessary to start the collaboration with the SMEs. Without any easy access to *in-situ* oceanic profiling lidar, the technique will not be fully accepted by the ocean color community and no advance in science will occur.

All the data should be open access, with standardized file format and metadata. A dedicated website should provide relevant and easy-to-use distribution tools, with near real time data visualization. A section on data product description and documentations with simple infographics on the methods of measurement are vital to target a large audience. And finally, an interactive platform where scientists and end-users can exchange ideas, give feedbacks, ask for specific needs, would be very appropriate.

In term of education, to our knowledge, the lidar and polarimetry techniques are not included in Master programs for Ocean Optics and related fields. In order to increase awareness of oceanic profiling lidar, the theory and practical use of the instrument must be included in their curriculum. The same should also occur during summer schools, such as the one organized by the University of Maine or the one organized by the International Ocean Color Coordinating Group. These Summer Schools are attended by Msc/PhD students and early career scientists working on ocean color. If we want future scientists in the field to tackle the use of lidar and polarimetry techniques, we need to include classes on these topics during these summer schools.

CONCLUSION AND PERSPECTIVES

Passive radiometric space-borne observations of the ocean color allow for the estimation of the optical properties and concentration of the marine particles, weighted- over the first meters near the surface of the ocean. These observations are available on a 2+-day global coverage basis for the past 20 years. It is now time to go beyond these observations to get access to (1) the profiles of these parameters through the first 3 optical depths and (2) information about the shape and concentration of these marine particles. To do that, the ocean color community must use other observational techniques that have been widely used for the study of the aerosols and clouds: Lidar and polarimetry.

While these techniques have sporadically been used for ocean studies inr the past 30 years, they did not get as much as attention in the ocean community as in the aerosol/clouds community for various reasons (including the unavailability of *in-situ* and space-borne instruments dedicated to the ocean). With new instruments (*in-situ* and potentially, spaceborne), the time is for the ocean color community to embrace the scientific potential of these techniques. To make it possible for the community to more thoroughly exploit the science benefits of these techniques, we recommend the following steps be taken:.

Ocean Lidar Recommendations

- Development of compact, cheap and easy to deploy elastic backscatter and HSRL lidar for shipborne and airborne ocean-profiling applications. The ocean-profiling lidars are currently limited to one-off instruments and are not commercially available. Recent technological advances in lasers and detectors show promise for reducing the size, power, and cost of ocean profiling lidars. Collaboration with small and medium companies is necessary to take advantage of these technologies and make these instruments available to research laboratories for deployment on field campaigns.
- Development of a spaceborne HSRL with 355 and 532 nm wavelengths and a fluorescence sensor at 684 nm. The current CALIOP lidar instrument on-board the CALIPSO satellite has a coarse vertical resolution that prevents acquisition of useful depth-resolved information. A future space mission should have a vertical resolution of 3 meters or less. Ideally, this spaceborne lidar should flown in an orbit synergistic with those of future ocean color instruments.
- Development of radiative transfer code to simulate the laser path for diverse oceanic water types. Studies on the lidar waveform are necessary for understanding the impact of the concentrations of marine particles on the shape and intensity of the lidar signal.

Ocean Polarimetry Recommendations

- Radiative transfer codes are as good as their inputs. In order to understand the theoretical framework of polarimetry in the ocean a suite of instruments need to be developed to better characterize the input to radiative transfer. Due to the lack of understanding hydrosols morphology and composition, instruments that measure their microphysical properties (particle size distribution, shape, internal structure, refractive indices of their internal components) and/or their full (4 × 4) scattering matrices are necessary to close this knowledge gap.
- Development of *in-situ* polarimeters, including those with hyperangular measurements, and hyperspectral capabilities from the UV to NIR. These instruments should be deployed in various water conditions to capture a large dynamic range of IOPs to allow for the development and validation algorithms.
- Investment in more field campaigns that include both *in-situ* and airborne polarimetry. These field campaigns should focus on ocean applications in scientifically interesting water and atmospheric conditions (i.e., in plankton bloom, coastal waters, and in the presence of absorbing aerosols) of which polarimetry can significantly contribute.
- Development of a spaceborne multi-angular polarimetric sensors designed for ocean applications. Pointing (gimbled) sensors are ideal for geometry targeting with high spatial resolution (1 km or better). The polarimetric accuracy should be high enough (better than 1% and highly preferably better than 0.5%) to capture the small polarized signal emerging from the ocean at the top of atmosphere.
- Development of the polarimetry atmospheric correction algorithms. These algorithms should have the capacity to retrieve both the intensity I and the polarization components (Q, U, and V) from the satellite measured Stokes vector.

Common Recommendations

- Ideally, the ocean polarimeter and ocean lidar airborne field campaigns should be coordinated together, and including hyperspectral spectroradiometer ocean color measurements in the VIS and UV. It may be beneficial to calibrate the airborne/oceanic polarimeter and hyperspectral (VIS and UV) instruments together in the lab, prior to and immediately after the field campaign studies are conducted.
- It is also recommended to provide training and education materials to students and early career scientists on ocean lidar and polarimeter techniques through the development of new courses in Masters and Summer School curricula. These courses will increase the exposure of these two important topics and will increase interest in the ocean optics community to produce novel research ideas.

AUTHOR CONTRIBUTIONS

CJ and AI coordinated the manuscript and wrote the introduction and conclusion. Jchu provided sub-section on Airborne Lidar. CJ, FA, DD, SV, ER, and IS contributed to sub-section *In-situ* Lidar. CH contributed to sub-sections High-Spectral-Resolution-Lidar and Lidar Satellite. EB, MJB, LL, and MB provided sub-section Lidar Satellite. LL and CJ contributed to section Outreach and Education. AI provided section Polarimetry Technique with the contribution of sub-sections Particle sizes and complex refractive index by LD-G, HL, and EB, sub-section Improved Glint Correction by LR and RF, sub-section Simultaneous Retrieval of Aerosol and Water-Leaving Radiance by MG, sub-section Fully Coupled AO RT Models by KS and SS, and sub-section In-Elastic Scattering VRT by P-WZ. KK provided **Table 3**. BC and JCho provided parts of section Measurement Principle. SS contributed to the introduction, sections Measurement Principle, Fully Coupled AO RT Models, Previous, Current and Future Missions, and the conclusion. BF, DG, OH, JCho, LR, KS, SS, ZA, JW, AD, OK, VM, XH, and P-WZ contributed revisions throughout section Polarimetry Technique.

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Satellite Salinity Observing System: Recent Discoveries and the Way Forward

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Advances in L-band microwave satellite radiometry in the past decade, pioneered by ESA's SMOS and NASA's Aquarius and SMAP missions, have demonstrated an unprecedented capability to observe global sea surface salinity (SSS) from space. Measurements from these missions are the only means to probe the very-near surface salinity (top cm), providing a unique monitoring capability for the interfacial exchanges of water between the atmosphere and the upper-ocean, and delivering a wealth of information on various salinity processes in the ocean, linkages with the climate and water cycle, including land-sea connections, and providing constraints for ocean prediction models. The satellite SSS data are complimentary to the existing *in situ* systems such as Argo that provide accurate depiction of large-scale salinity variability in the open ocean but under-sample mesoscale variability, coastal oceans and marginal seas, and energetic regions such as boundary currents and fronts. In particular, salinity remote sensing has proven valuable to systematically monitor the open oceans as well as coastal regions up to approximately 40 km from the coasts. This is critical to addressing societally relevant topics, such as land-sea linkages, coastal-open ocean exchanges, research in the carbon cycle, near-surface mixing, and air-sea exchange of gas and mass. In this paper, we provide a community perspective on the major achievements of satellite SSS for the aforementioned topics, the unique capability of satellite salinity observing system and its complementarity with other platforms, uncertainty characteristics of satellite SSS, and measurement versus sampling errors in relation to *in situ* salinity measurements. We also discuss the need for technological innovations to improve the accuracy, resolution, and coverage of satellite SSS, and the way forward to both continue and enhance salinity remote sensing as part of the integrated Earth Observing System in order to address societal needs.

Keywords: salinity, remote sensing, Earth's observing systems, future satellite missions, SMAP, SMOS, Aquarius

INTRODUCTION: REMOTE SENSING OF SALTY OCEANS

Sea water is approximately a 3.5% salt solution (Durack et al., 2013; Pawlowicz et al., 2016), corresponding to a salinity of 35[1], the remaining 96.5% being freshwater. Wunsch (2015) finds the mean salinity of the entire ocean to be 34.78, with a standard deviation of only 0.37 and over 90% of sea water falling within the salinity range of 34 to 36. Despite this small range, salinity variations have a profound effect on global ocean circulation and Earth's climate and ecosystems. Ocean basins vary in terms of their salinity (**Figure 1**), with the Atlantic being the saltiest ocean and the Pacific the freshest (Gordon et al., 2015). These mean patterns are a response to the changes in the ocean circulation and the ocean water cycle – the net sum of precipitation, evaporation, and terrestrial river and groundwater runoff, as well as the formation and melting of glacial and sea ice. Excess input or deficit of freshwater impacts salinity signatures, the equivalent of floods and droughts on land (Schmitt, 2008; Schanze et al., 2010; Yu, 2011; Durack, 2015; Gordon, 2016), reflecting responses to the changing hydrological cycle associated with climate change (Curry et al., 2003; Boyer et al., 2005; Hosoda et al., 2009; Durack and Wijffels, 2010; Helm et al., 2010; Durack et al., 2012; Skliris et al., 2014; Vinogradova and Ponte, 2017).

As might be expected, the ocean hydrological cycle has the greatest impact on the ocean surface layer, but this signal, governed by ocean dynamics, runs deep and varies greatly across the ocean regimes as the surface water spreads into the full volume of the ocean through vertical and horizontal (or isopycnal and diapycnal) advective and diffusive processes (Ponte and Vinogradova, 2016).

Ocean salinity is not a passive tracer of ocean dynamics as salinity, along with temperature and pressure, is a component of the equation of state of sea water. Increased salinity increases density, unless offset by an increase in temperature. The ratio of the salinity to temperature impact on density changes with temperature, with salinity taking on a larger role in cold polar waters because the coefficient of thermal expansion diminishes as the temperature drops and the haline contraction coefficient increases with cooler temperatures. As salinity alters the density field, it influences horizontal pressure gradients of the flow as well as the vertical stability of the water column. Such changes, in turn, affect ocean currents and mixing, influencing the transport of oceanic properties such as heat, freshwater, nutrients, and carbon. Given its critical role in ocean dynamics, climate variability, the water cycle, and marine biogeochemistry, salinity is recognized as an essential climate variable within the Global Climate Observing System (GCOS) (Belward et al., 2016).

Observing salinity from space offers the advantages of global coverage and the ability to capture space and time scales not afforded by *in situ* platforms such as vessels, moorings, and Argo profiling floats. For example, the nominal sampling of the Argo array is one profile per 3° latitude × 3° longitude at 10-day intervals. There are generally very few Argo floats in marginal seas, coastal oceans, polar oceans, and in regions of large-scale divergence, where salinity variations have strong impacts on ocean dynamics, air-sea and ocean–ice interactions, and land-sea linkages (**Figure 2**). Salinity remote sensing complements the *in situ* salinity observing system by improving the capability to study mesoscale salinity variability (see sections "Improving Knowledge of Ocean Circulation and Climate Variability" and "Complementing the *in situ* Salinity Network") and land-sea linkages in the context of the water cycle and biogeochemical cycles (more in section "Opening the Window to Better Understand Earth's Water Cycle").

In the latter third of the 20th century, an impressive array of ocean information was derived remotely from orbiting satellites, but only in the 21st century have we gained satellite views of sea surface salinity (SSS). Satellite measurements have given us a near-global, synoptic view of SSS (e.g., **Figure 2**), opening a window to a fuller understanding of the global hydrological cycle, climate variability, ocean circulation, and marine biochemistry. The satellite missions pioneering salinity remote sensing include the ESA Soil Moisture and Ocean Salinity (SMOS) Mission (2009-present) (Reul et al., 2012); the joint NASA/CONAE Aquarius/SAC-D mission (June 2011–June 2015) (Lagerloef et al., 2013); and the NASA Soil Moisture Active Passive (SMAP) mission (January 2015-present) (Entekhabi et al., 2014; Tang et al., 2017).

All three satellite SSS missions provide measurements of the surface brightness temperature at L-band radiometric frequencies (∼1.4 GHz), a frequency band in which brightness temperature has good sensitivity to SSS in warm (>5°C) waters (Klein and Swift, 1977). Aquarius and SMAP have similar active-passive designs, with an active L-band radar scatterometer integrated with the passive L-band radiometer. SMOS is solely based on passive L-band interferometric radiometry. For all three missions, the process of retrieving SSS from brightness temperatures involves removing various, non-salinity contributions related to direct and ocean-reflected extra-terrestrial radiations from the Sun and galaxy (e.g., Le Vine et al., 2005; Reul et al., 2007, 2008), as well the noise from sea surface temperature (SST) and ocean surface roughness (e.g., Yueh et al., 2010, 2013, 2014; Meissner et al., 2014, 2018). The latter is one of the dominant errors sources in the SSS retrieval budget that must be precisely removed. While the L-band radar on Aquarius was used to correct for the surface roughness effect, SMAP's active radar ended operation 3 months after launch. Consequently, the correction of the surface roughness effect in both SMOS and SMAP SSS retrievals rely on ancillary wind data and on roughness information inferred from polarized L-band brightness temperature. For SSS retrievals, all three L-band missions use ancillary SST measurements to remove thermal effects on brightness temperature measurements. The adequacy and accuracy of ancillary wind and SST measurements are very important to the uncertainties of SSS retrievals.

All three SSS-observing satellites are in sun-synchronous polar orbits with high inclinations, allowing near-global coverage including the polar oceans. The missions differ in their spatial

[1]Practical Salinity Scale 1978 (PSS-78) are used, following UNESCO guidelines "*The Practical Salinity Scale 1978 and the International Equation of State of Seawater 1980.*" Although salinities measured using PSS-78 do not have units, the suffix "pss" is sometimes used in the text and figures to distinguish the values of salinity, rates, and variance.

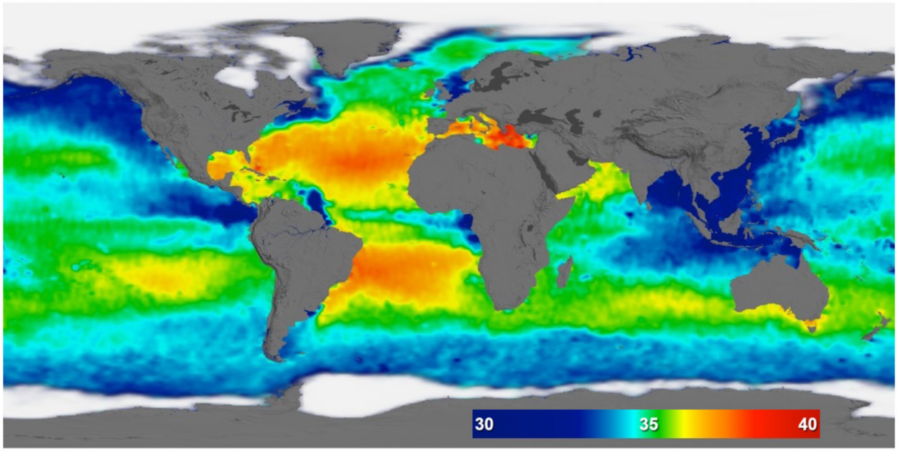

FIGURE 1 | Example of synoptic, near-global salinity coverage from satellite observations showing annual mean sea surface salinity patterns based on observations from the Aquarius mission during 2011–2014. Credit: NASA.

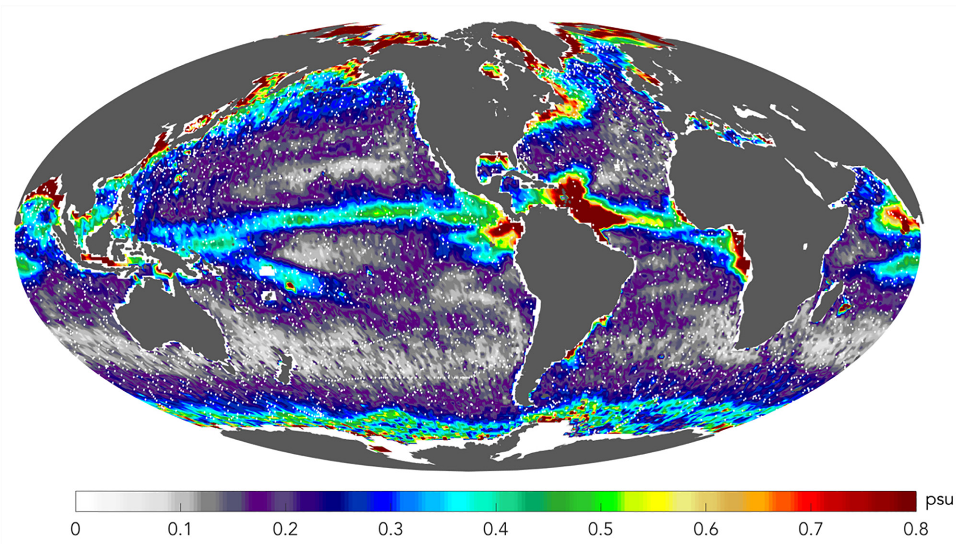

FIGURE 2 | Variability in space-borne sea surface salinity during 1 year (colors) superimposed with locations of currently operational Argo floats (white dots). Notice that regions of high variability of >0.2 are either not sampled or poorly sampled by Argo, including coastal oceans, western boundary currents, the Indonesian Seas, outlets of major rivers (Amazon, Niger, and Congo), as well as the Southern and Arctic Oceans.

and temporal coverage. SMOS has an average 43-km spatial resolution with an 18-day near-repeat cycle and a 3–5 day revisit time. Aquarius had a 100–150 km spatial resolution and a 7-day exact repeat. SMAP has a 40-km spatial resolution and an 8-day repeat with a 2–3 day revisit time. Therefore, all three missions provide synoptic measurements of SSS over the global ocean at spatial and temporal scales much finer than those afforded by the Argo array; consequently, satellite SSS measurements are able to resolve higher-frequency signals (e.g., tropical instability waves) that are difficult for *in situ* data to capture.

Satellite SSS measurements serve a broad user community from scientific research to applications. These include studies of ocean dynamics, the ocean's role in climate variability, linkages with the hydrological and biogeochemical cycles, ocean state estimation, ocean forecasts and climate predictions, and environmental assessments associated with extreme events such as hurricanes and flooding. The science and application drivers of satellite SSS in support of these user communities are discussed in Sections "Scientific Drivers for Satellite Salinity" and "Application Drivers for Satellite Salinity."

The objective of this review is to provide community inputs to OceanObs'19 on the issues related to the space-based salinity observing system. In what follows, we (1) summarize the achievements and current capabilities of the satellite SSS observing system; (2) describe science and application drivers, user communities of satellite SSS for the coming decade, and their associated requirements; (3) address the necessity and benefits of integrating satellite SSS with other observing systems and models; and (4) discuss the strategy that addresses capability gaps in the coming decade to improve support of end users.

SCIENTIFIC DRIVERS FOR SATELLITE SALINITY

Improving Knowledge of Ocean Circulation and Climate Variability

Salinity remote sensing has significantly improved our ability to study large-scale ocean processes. Examples include the studies that brought new knowledge about tropical instability waves (Lee et al., 2012, 2014; Yin et al., 2014), Rossby waves (e.g., Menezes et al., 2014; Banks et al., 2016), dynamics of the subtropical salinity maximum and tropical salinity minimum zones (e.g., Hasson et al., 2013; Bingham et al., 2014; Hernandez et al., 2014; Yu, 2014; Gordon et al., 2015; Guimbard et al., 2017; Hasson et al., 2018), and climate variability (Delcroix, 1998; Delcroix et al., 2007; Du and Zhang, 2015; Vinogradova and Ponte, 2017). These studies are among many other that have demonstrated that the space-time resolution and coverage of salinity satellites provide a unique perspective, enhance the ocean observing network, and complement *in situ* salinity observations.

For example, one of the early scientific results based on satellite SSS is the discovery of new features of tropical instability waves. Tropical instability waves play an important role in ocean mixing, cross-equatorial transport, climate variability, and biochemistry, and have been studied extensively using various satellite and *in situ* observations since they were discovered in the late 1970s (e.g., Legeckis, 1977; Chelton et al., 2000). Complementing previous studies, satellite SSS observations revealed previously unreported features of tropical instabilities waves, including the dependence of the wave propagation speed on latitude and the phase of the El Niño-Southern Oscillation (ENSO) (Lee et al., 2012; Yin et al., 2014). The findings provided new insights into the inter-hemispheric exchange of freshwater, with implications on ocean circulation and the hydrological cycle (Lee et al., 2012).

The high temporal resolution of satellite SSS enabled a better understanding of large-scale intra-seasonal phenomena (e.g., Subrahmanyam et al., 2018), including the Madden-Julian Oscillation (MJO) – the dominant climate mode at sub-seasonal time scales in the tropics that impacts the global weather and climate (Zhang, 2005). Satellite SSS measurements enable characterization of the SSS signature associated with MJO and the associated impacts on surface density variations (Grunseich et al., 2013; Guan et al., 2014; Li et al., 2015), emphasizing the role of upper-ocean dynamics in regulating MJO.

Satellite salinity has also improved our understanding of seasonal-to-interannual variability. For example, satellite SSS measurements revealed new features of annual Rossby waves in the South Indian Ocean associated with coupled air-sea and surface–subsurface interactions (Menezes et al., 2014). On interannual time scales, satellite SSS measurements demonstrated their value in helping to characterize the structure of the Indian Ocean Dipole (IOD) (Durand et al., 2013; Du and Zhang, 2015), which is known to influence regional weather and climate (Saji et al., 1999). The superior spatio-temporal sampling of satellite SSS helped establish a robust relationship between SSS and the IOD (Du and Zhang, 2015). Another example of new insight enabled by satellite SSS is the relationship between the large-scale tropical fresh pools in the tropical Pacific with ENSO-induced precipitation and oceanic transport associated with mesoscale eddies (Alory et al., 2012; Guimbard et al., 2017; Hasson et al., 2018; **Figure 3**). The two examples of the linkages of SSS with climate modes (ENSO and the IOD) demonstrate the potential of satellite SSS to improve the representation of climate variability in ocean models and related forecasts, e.g., through SSS data assimilation.

Decadal changes in salinity serve as an important indicator of the internal climate fluctuations (as opposed to externally caused variability due to anthropogenic and natural forces), and help explain longer-term secular changes in the climate system (e.g., Friedman et al., 2017). Informed by satellite salinity data through data assimilation and synthesis with other ocean observations and dynamical constraints, Vinogradova and Ponte (2017) reported significant large-scale SSS trends as yet more evidence of global climate change. Some portion of the decadal fluctuations in surface salinity, however, is associated with natural climate variability, such as the Interdecadal Pacific Oscillations (IPO, **Figure 4**), which effectively masks long-term salinity trends that are related to secular changes in the forcing.

Opening the Window to Better Understand Earth's Water Cycle

Over the global ocean, the most significant moisture sources are located in the subtropical oceans (e.g., **Figure 5**), where the descending branch of Hadley circulation suppresses convection and precipitation, while prevailing trade winds promote evaporation (Gimeno et al., 2012). To maintain the global water balance (Schmitt, 1995; Trenberth and Guillemot, 1995; Stohl and James, 2005; Trenberth et al., 2007), this excessive flux of moisture from the ocean to the atmosphere is transported away from the subtropics to the tropical oceans over the ITCZ (Inter Tropical Convergence Zone), the mid-latitude storm-track region, and over land as terrestrial precipitation (Gimeno et al., 2010; Lagerloef et al., 2010; Schanze et al., 2010; van der Ent et al., 2010).

Observational and modeling evidence suggests that in response to the warming climate, surface freshwater fluxes over the oceans have developed a distinctive pattern of change (**Figure 5**), where dry subtropical areas are becoming drier and wet tropical areas becoming wetter (Stott et al., 2008; Cravatte et al., 2009; Durack and Wijffels, 2010; Helm et al., 2010; Durack et al., 2012; Terray et al., 2012; Skliris et al., 2014, 2016; Vinogradova and Ponte, 2017; Zika et al., 2018). For example, from the ECCO state estimate and **Figure 5**, over the past two decades the ocean water cycle amplified by about 5% on average, consistent with surface warming of about 0.65°C since 1992. That translates to a change of 7.6%$^\circ C^{-1}$, which is close to that

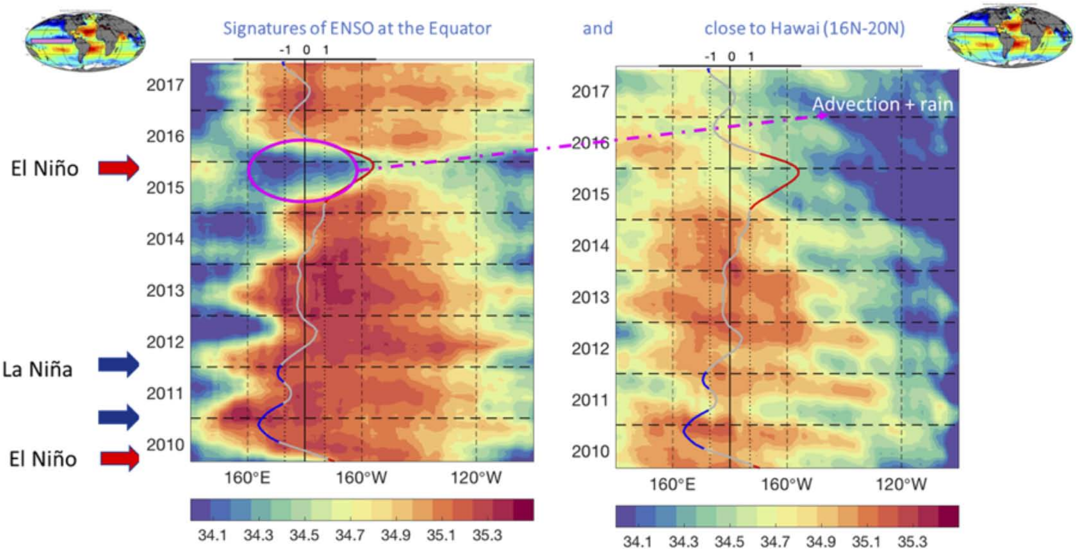

FIGURE 3 | Satellite SSS are used to monitor large-scale events, including ENSO-induced fresh anomalies that are propagated by mesoscale processes. Shown here are time-longitude plots of SMOS SSS, averaged between (left) 2°S and 2°N and (right) 16°N and 20°N. NINO3.4 index is shown on top of all plots, blue during La Nina and red during El Nino. For the first time, strong negative salinity anomalies that stretch over the tropical Pacific and reach the Hawaii islands have been detected, induced by an extreme El Nino event of October 2015–2016. Modified from Hasson et al. (2018).

predicted by the thermodynamics and the Clausius–Clapeyron relation of 7%°C^{-1}. This intensification of the hydrological cycle is often linked to corresponding changes in surface salinity: the changes in the amount of freshwater leaving and entering the oceans are expected to leave its "fingerprints" detectable in ocean variables, with SSS variability reflecting the changes in the ocean water cycle (Schmitt, 2008; Durack and Wijffels, 2010; Lagerloef et al., 2010; Yu, 2011; Durack et al., 2012; Terray et al., 2012; Durack, 2015; Friedman et al., 2017). Although a direct link between changes in surface salinity and changes in freshwater flux is rather difficult to observe on timescales relevant to the satellite observational records (Vinogradova and Ponte, 2013a, 2017; Hasson et al., 2014; Yu, 2015; Guimbard et al., 2017), the research community consensus, outlined in Durack et al. (2016), is that ocean salinity can be effectively used as an implicit, rather than explicit, indicator of changes in the water cycle.

An important application of satellite salinity is connecting the terrestrial and marine water reservoirs, with an aim to close the global balance of water fluxes and flows. Combined with other measurements, satellite SSS observations allow one to trace large riverine waters over great distances and reconstruct the complete lifecycle of hydrological events, from rainfall to river discharge on land and then to river plume formation, mixing, and advection in the ocean (Fournier et al., 2011; Bai et al., 2013; Gierach et al., 2013; Reul et al., 2013; Grodsky et al., 2014; Guerrero et al., 2014; Zeng et al., 2014; Fournier et al., 2015, 2016, 2017a,b; Korosov et al., 2015). These studies improved our understanding of ocean–land interactions by elucidating the impacts of rivers on the buoyancy of the surface ocean layer, on circulation patterns via horizontal density gradients, on marine biochemistry, the carbon cycle, and on ecological activity (Muller-Karger et al., 1988; McKee et al., 2004). In addition to tracing the origin and fate of freshwater signals, satellite SSS has also been used to gauge the influence of rivers on regional climate and oceanic productivity (Fournier et al., 2017a), as well as the impacts of the river-influenced warming on the upper ocean during the Atlantic hurricane season (Fournier et al., 2017b).

New Opportunities in Mesoscale Oceanography

A tremendous advantage of satellite SSS observations is their synoptic view of oceanic mesoscale haline features associated with fronts and eddies down to scales on the order of 100 km (e.g., Maes et al., 2014; Reul et al., 2014a; Kolodziejczyk et al., 2015; Fournier et al., 2016, 2017b; Isern-Fontanet et al., 2016; Da-Allada et al., 2017; Grodsky et al., 2017; Melnichenko et al., 2017). The capability to systematically sample 40–100 km scales every 4 days is unachievable by other salinity observing platforms, including the Argo program. Although smaller eddies are still difficult to detect by the current generation of salinity-measuring satellites, the capability to monitor salinity features associated with the larger eddies is a breakthrough both in terms of spatial and temporal sampling. As an illustration, **Figure 6** compares complex current and frontal systems depicted by satellite SSS with those inferred from Argo. Mesoscale fronts are important components of ocean dynamics because they are associated with strong current instability and ocean mixing. Oceanic fronts have enhanced vertical velocity, where the deep ocean exchanges properties with the surface mixed layer (Pollard and Regier, 1992). Enhanced vertical nutrient fluxes at fronts act to increase phytoplankton production and biomass, funneling nutrients through different trophic levels, including to commercially important fish (Woodson and Litvin, 2015).

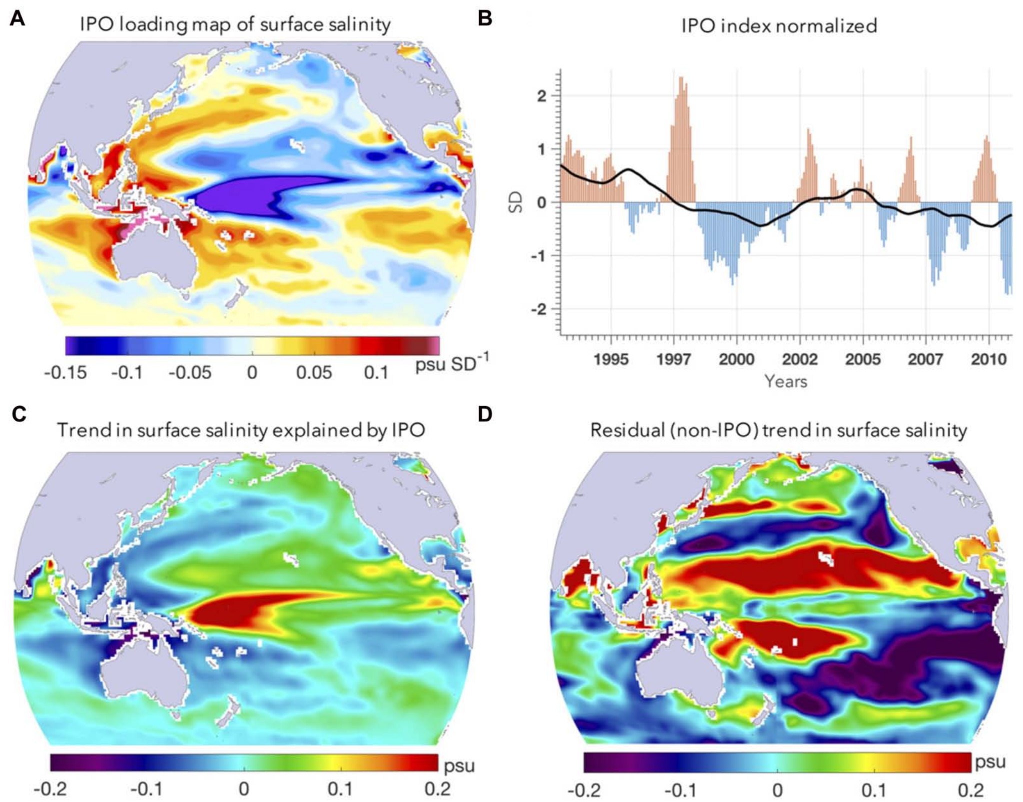

FIGURE 4 | Surface SSS trends as indicator of internal climate variability. Tropical changes in SSS over the past 20 years are partly attributed to Interdecadal Pacific Oscillation (IPO), explaining strong surface salinification in the Pacific warm Pool (red) despite an increase of flux of freshwater into the ocean (blue in **Figure 5**). Based on multi-platform salinity estimate ECCO that combines satellite and in situ data with dynamical constraints. Shown here are **(A)** Expression of the IPO loading pattern in surface salinity, computed by linearly regressing monthly ECCO salinity anomalies upon **(B)** the IPO time series in normalized units of standard deviation. **(C)** Trends in the IPO loading salinity patterns. **(D)** Residual trends after the relevant IPO loading pattern is removed. Trends in panels **(C,D)** represent the total change over 20 years, computed as a linear trend multiplied by the period length. Adapted from Vinogradova and Ponte (2017). Figure© Copyright July 2017 AMS.

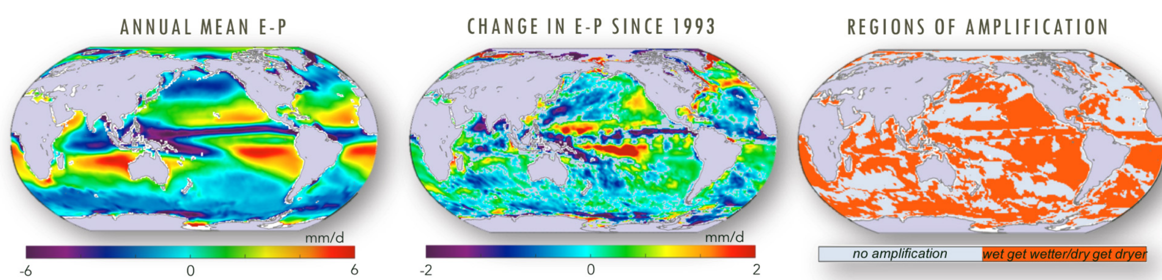

FIGURE 5 | Linking salinity to the global hydrological cycle is one of scientific drivers of satellite SSS. Shown here are mean patterns of the ocean water cycle and its amplification in the last two decades based on the ECCO ocean state estimate. Left: average rates at which freshwater enters (blue) or leaves (red) the ocean via the processes of precipitation (P) and evaporation (E); Middle: trends in E-P; blue (negative) means that the ocean received more freshwater since 1993. Right: Amplification of the ocean water cycle, computed as a slope of the linear regression between the anomalies and trends in E-P. Pattern amplification is shown as orange, otherwise is shaded gray. In many ocean regions, pattern amplification follows the wet gets wetter/dry gets drier paradigm, as more freshwater is brought to wet regions (e.g., blue colors match blue in the tropics), or more freshwater is removed from dry regions (e.g., red colors match red in the United States west coast. If averaged over the globe, the ocean water cycle has amplified by 5% since 1993. See Vinogradova and Ponte (2017) for details.

While satellite SST observations have long been available to study oceanic fronts and eddies, satellite SSS observations bring a new perspective. By discovering SST/SSS decoupling in the frontal regions (Kolodziejczyk et al., 2015; Kao and Lagerloef, 2018), we are redefining the role of salinity in density variability, thermohaline circulation, and in the energy balance of the upper ocean. Satellite SSS observations also improved the ability to study the kinetic energy variability of

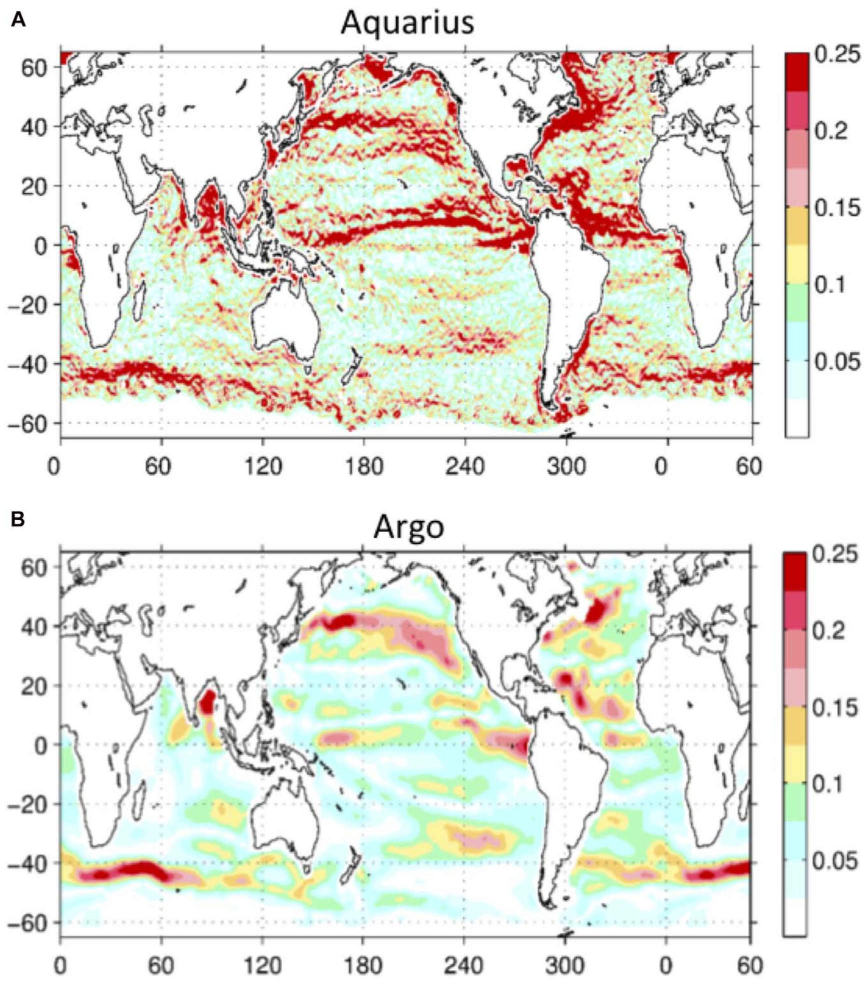

FIGURE 6 | Salinity SSS resolve fine mesoscale features, such as fronts and eddies, that are not depicted by blurry maps computed based in situ-based products; **(A)** Map of the horizontal SSS gradient magnitude (pss/100 km) based on the September 2011 mean SSS field from the Aquarius satellite. The oceanic frontal zones are associated with high values of SSS gradient (red). **(B)** The same as in panel **(A)** but from the Argo-derived SSS. Modified from Melnichenko et al. (2016).

ocean circulation (Gordon and Giulivi, 2014; Reul et al., 2014a; Sommer et al., 2015; Busecke et al., 2017; Melnichenko et al., 2017), elevating the role of eddy transport in the ocean freshwater balance, even in the interiors of the subtropical gyres where eddies have historically been thought to have a negligible effect.

Unlocking Space-Based Ocean Biogeochemistry

Expanding upon the conventional physical oceanography boundaries, satellite SSS data has been recently exploited in the biogeochemistry domain (e.g., Lee et al., 2006; Lefèvre et al., 2014; Ibánhez et al., 2017), addressing studies of ocean acidification and the carbon cycle. Since the industrial revolution, the oceans have absorbed about 40–50% of the anthropogenic carbon dioxide (CO_2) emissions to the atmosphere (Sabine et al., 2004; Khatiwala et al., 2009), mitigating the impact of global warming. However, studies have suggested that the oceanic carbon sink may have been decreasing during the last 50 years (Canadell et al., 2007; Le Quere et al., 2009), which can significantly impact future atmospheric CO_2 levels and the global climate.

Absorption of CO_2 into the ocean reduces the ocean pH and the concentration of carbonate ions. The overall process is referred to as ocean acidification, which has profound socio-economic consequences. In order to characterize the overall marine carbonate system, the partial pressure of CO2 in surface seawater (pCO_2), the total alkalinity, the dissolved inorganic carbon, and the pH itself must be known. However, the difficulty in quantifying these parameters is due to the scarcity of biochemical *in situ* observations, such as the SOCAT dataset (Bakker et al., 2016). In this regard, satellite SSS data (together with additional observables) offers a path forward to monitor ongoing changes in ocean acidification by exploiting synoptic satellite observations to produce global assessments of ocean surface pH and alkalinity (Brown et al., 2015; Land et al., 2015; Sabia et al., 2015a; Salisbury et al., 2015; Fine et al., 2017).

Similar to salinity, alkalinity is sensitive to freshwater flux. Consequently, alkalinity features resemble the mean surface

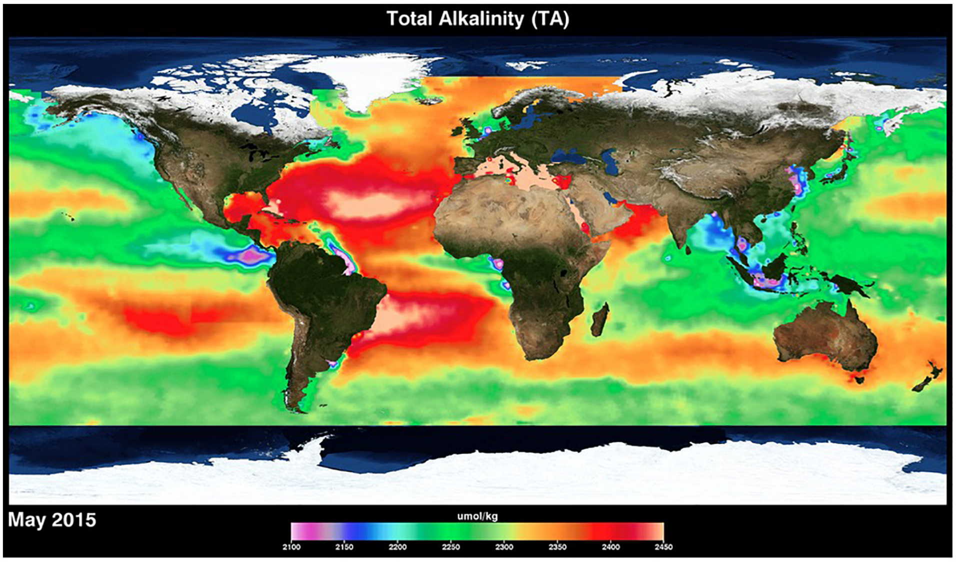

FIGURE 7 | Satellite SSS data becoming key in monitoring the marine carbonate system, enabling the development of novel space-based ocean acidification. Shown here is monthly surface total alkalinity derived using Aquarius SSS. Source: NASA.

salinity distribution (**Figure 7**), with salinity variations explaining 80% of total alkalinity variability in the subtropics. That makes salinity a valuable proxy for surface alkalinity. Taking advantage of global, high-resolution satellite SSS measurements, it is now possible to derive space-based assessments of ocean acidification and observe how it changes over time (Fine et al., 2017). The results suggest a tendency of generally increasing alkalinity in the subtropics (along with increasing temperature and salinity), reinforcing the assessment of ocean acidification from uptake of atmospheric CO_2.

Advancing Climate Modeling and Ocean State Estimation

A powerful approach in modern oceanography is to combine observations and models – be they ocean-only or fully coupled simulations – using various data assimilation techniques. More than a decade of experience with assimilating *in situ* salinity data from surface moorings and three-dimensional measurements from Argo, ships, etc., has demonstrated that the resulting synthesis product can provide a more accurate estimate of the ocean state than observations or model alone (Stammer et al., 2002a,b, 2016; Wunsch and Heimbach, 2013), including better handling of climate simulations of air-sea coupling and resulting changes in ocean circulation. By observing the top centimeter of the water column globally, dense satellite SSS data provides additional constraints on interfacial exchanges of water between the atmosphere and the upper-ocean, helping close the global freshwater budget, improve estimates of the ocean state, and inform future climate projections. If performed in a dynamically consistent way, the data assimilation process will not only improve the model's salinity fields and derivatives such as circulation fields and sea level, but will also help better constrain the mean and time-varying surface net freshwater forcing and air-sea fluxes (Stammer et al., 2004; Carton et al., 2018), which are some of the least constrained parameters in climate models leading to large uncertainties in model simulations.

Assimilation of satellite SSS data helped improve the accuracy of model salinity and air-sea fluxes within the Estimating the Circulation and Climate of the Ocean (ECCO) solution (Köhl et al., 2014). By providing additional constraints on model freshwater fluxes, the assimilation of satellite SSS reduced uncertainties in surface forcing, producing a better correspondence between models and independent satellite-based air-sea fluxes, and reduced known model salinity biases with respect to *in situ* measurements.

Today, the ECCO framework reconciles various salinity observations from different platforms (as well as observations for other state variables) using dynamical constraints, and produces an accurate, multi-platform salinity estimate for climate research (**Figure 8**; see also Vinogradova et al., 2014; Fukumori et al., 2018; Vinogradova, 2018). Such a synergistic, dynamically consistent view becomes an additional component of the salinity observing network – a component allowing one to tease out the causes and effects of recent salinity changes from the interplay between the three-dimensional ocean circulation, transports of salt and freshwater, and surface forcing.

APPLICATION DRIVERS FOR SATELLITE SALINITY

In addition to science priorities, there is a wide range of emerging societal applications and end users of salinity remote sensing data, including hurricane monitoring; prediction of rain, floods, and droughts; understanding climate modes of variability; and improving ocean and ecological forecasting.

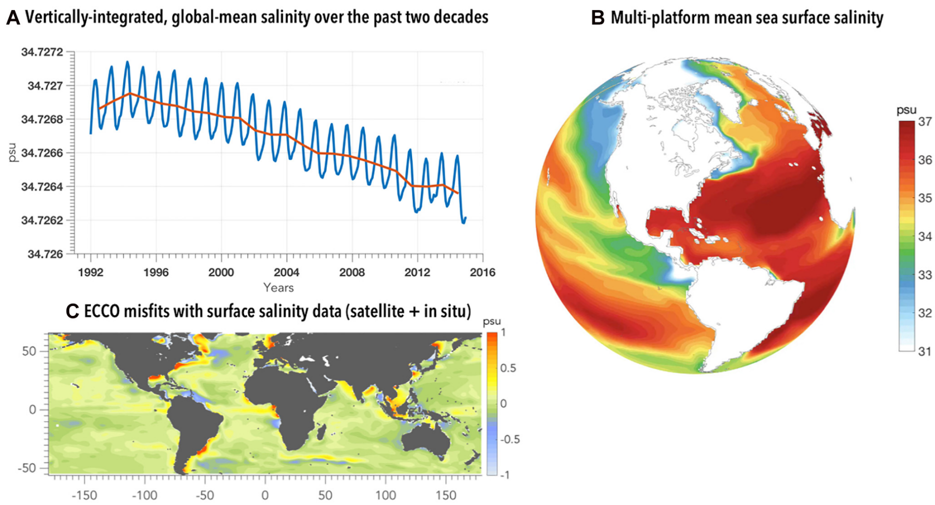

FIGURE 8 | Information from satellite SSS data improves climate models and ocean state estimates in systems like ECCO. **(A)** Vertically integrated, globally averaged salinity over the past two decades computed from monthly (blue) and annual (red) values. The global mean salinity value is 34.72, with a narrow range over the oceans. Notice a global freshening trend, with a drop of about −0.0005 pss/20 years, which represents the net transfer of mass into the ocean due to freshwater exchange. The value is consistent with the global-mean mass variations observed by GRACE, equivalent to −0.0004 pss/20 years. **(B)** Annual mean patterns in surface salinity from ECCO, featuring salty subtropics and fresher tropical and high-latitude regions, a generally saltier Atlantic and a fresher Pacific ocean. **(C)** ECCO/data misfits at the model surface (satellite and in situ), with distribution close to Gaussian (not shown). In most ocean regions, the misfits are less or around 0.1 of the observed averaged (green), apart from several coastal regions with higher systematic biases. Adapted from Vinogradova (2018).

Hurricane Monitoring

In monitoring hurricanes, it is sea surface temperature and sea surface height that first come to mind as measures of ocean heat content available for storm formation and intensification. However, in recent years, there has been growing interest in the role and response of SSS in hurricane intensification and passage. In regions where salinity is an important driver of vertical stratification, such as tropical oceans near the outflows of major rivers, SSS can impact air–sea interactions. In these regions, low SSS helps the formation and maintenance of a thin surface mixed layer, along with an isothermal salinity-stratified "barrier" layer between the surface mixed layer and colder thermocline water (Lukas and Lindstrom, 1991; Pailler et al., 1999; Vinaychandran et al., 2002; Rao and Sivakumar, 2003; Balaguru et al., 2012, 2015, 2016).

On one hand, the barrier layer helps trap solar radiation in the surface layer (Ffield, 2007; Foltz and McPhaden, 2008; Vizy and Cook, 2010; Grodsky et al., 2012; Fournier et al., 2017a), leading to elevated SSTs that are favorable for deep atmospheric convection and strong rainfall (Shenoi et al., 2002). On the other hand, barrier layers can prevent vertical mixing and entrainment of cool thermocline water into the mixed layer (Vialard and Delecluse, 1998; Vincent et al., 2012; Thadathil et al., 2016), thus further supporting hurricane intensification (Cione and Uhlhorn, 2003; Sengupta et al., 2008; Balaguru et al., 2012; Grodsky et al., 2012; Neetu et al., 2012; Reul et al., 2014b).

Satellite SSS measurements are able to capture haline wakes that form after hurricane passage, particularly in regions where upper-ocean stratification is driven by salinity (**Figure 9**). By analyzing hundreds of storms in the Atlantic Ocean, recent studies (Grodsky et al., 2012; Reul et al., 2014b; Fournier et al., 2017a) demonstrate the effect of barrier layers on hurricane intensification, emphasizing the role of salinity stratification in mixed-layer dynamics and the use of satellite SSS data as a new resource to study the ocean response to tropical cyclones.

Toward Better ENSO Forecasting

The ENSO cycle with alternating El Niño and La Niña events is the dominant year-to-year climate signal on Earth. ENSO originates in the tropical Pacific through interactions between the ocean and the atmosphere, but its environmental and socioeconomic impacts are felt worldwide, ranging from agriculture, to marine ecosystems, to human health (Horel and Wallace, 1981; Glantz, 2001). Efforts to understand the causes and consequences of ENSO reveal the breadth of ENSO's influence on the Earth system and the potential to exploit its predictability for societal benefit (McPhaden et al., 2006; National Academies of Sciences, Engineering, and Medicine, 2016).

One key component of ENSO predictability is the impact of freshwater flux in the tropics on coupled modeling. Representation of tropical precipitation, including the double-ITCZ biases (e.g., Adam et al., 2018), is rather poor in the current generation of coupled models (Wang et al., 2010), with implications for coupled forecast results. Systematic misrepresentation of precipitation results in erroneous surface forcing, impacting the correctness of the initialization and forecasting of ocean salinity. Inaccurate salinity, in turn, leads to the misrepresentation of mixed-layer density, barrier-layer thickness, and upwelling in the ocean model, as well as subsequent ramifications for ENSO predictions from the coupled model.

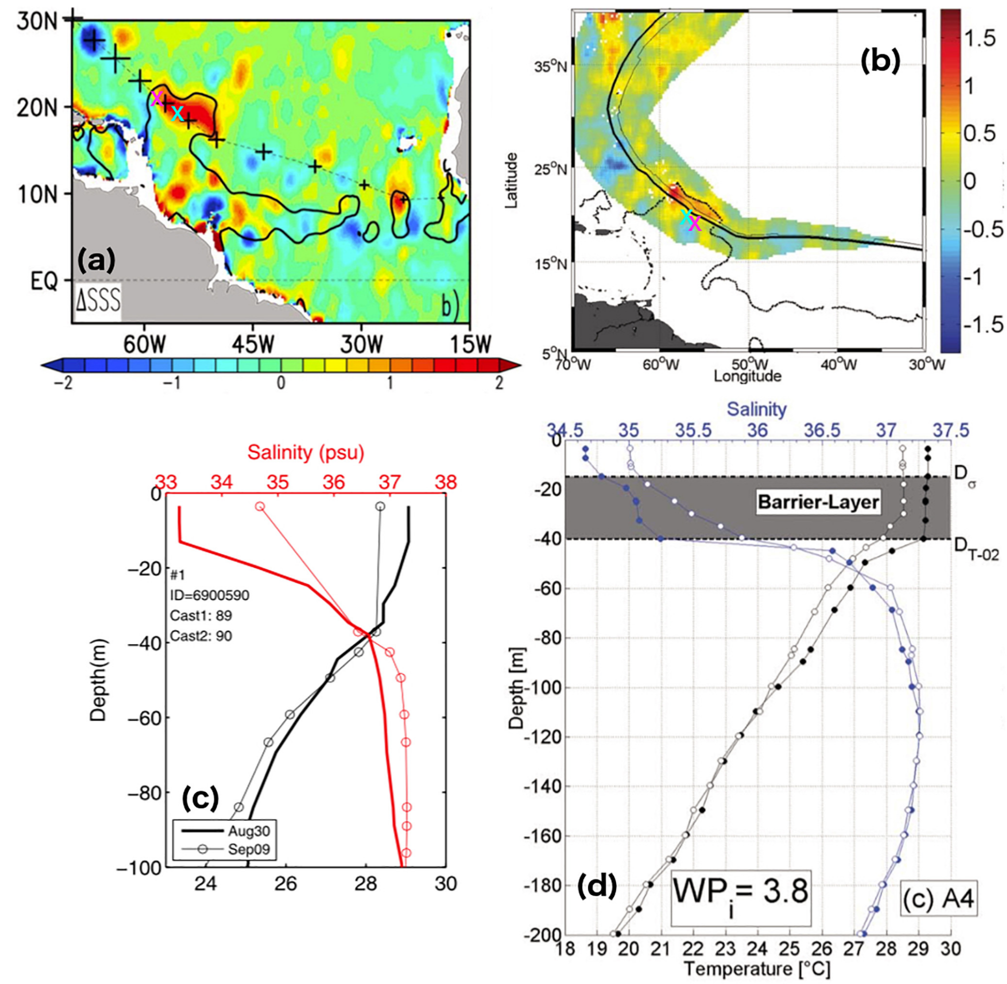

FIGURE 9 | Monitoring hurricanes using satellite SSS data from panel **(a)** Aquarius and **(b)** SMOS, respectively, showing differences from after versus before Katia and Igor hurricane passages in the Atlantic Ocean. **(c,d)** Argo salinity profiles before and after the hurricanes passage. The location of the Argo floats are marked by magenta and cyan crosses in panels **(a,b)**. Figure sources: Grodsky et al. (2012) and Reul et al. (2014b). Reproduced under license agreement 4445231502401 and 4445231097796.

Recent studies demonstrate that using salinity observations is a promising tool for understanding and expanding the limits of ENSO prediction (Maes et al., 2005; Hackert et al., 2011, 2014; Zhu et al., 2014). In practice, accounting for the salinity structure provides better estimates of the barrier layer thickness and mixed-layer dynamics, including the increase in stability of the mixed layer that allows the wind forcing to be more efficient. The latter, in particular, enhances the ocean's sensitivity to Kelvin wave forcing, resulting in the overall improvement of coupled ENSO predictions.

Predicting Terrestrial Floods and Droughts

Oceans are the major suppliers of moisture to land and significantly impact terrestrial precipitation, including hydroclimate extremes such as floods, droughts, and water shortage (Gimeno et al., 2013).

Given the limited water-holding capacity of the land surface, intense and persistent precipitation events cannot be sustained by local moisture recycling (Brubaker et al., 1993; Trenberth, 1998, 1999; Koster et al., 2004; Dirmeyer et al., 2009) and for the majority of extreme rainfall events over land, the moisture supply has oceanic origins (Zhou and Yu, 2005; Weaver and Nigam, 2008; Chan and Misra, 2010; Cook et al., 2011; Kunkel et al., 2012; Li et al., 2013). Correspondingly, any deficit in oceanic moisture supply usually leads to drought and water shortage (Weaver et al., 2009a,b; Seager and Vecchi, 2010). Thus, the oceanic water cycle, by modulating the regional moisture balance, significantly affects hydroclimate extremes on land.

The close linkage between the oceanic and terrestrial components of the Earth's water cycle, along with the sensitivity of SSS to the oceanic component, suggests that SSS can be utilized as a predictor of precipitation on land. Recent evidence has shown how salinity information can add great value to the early-warning systems of hydrology-related natural disasters. In particular, the linkage between the oceanic water cycle,

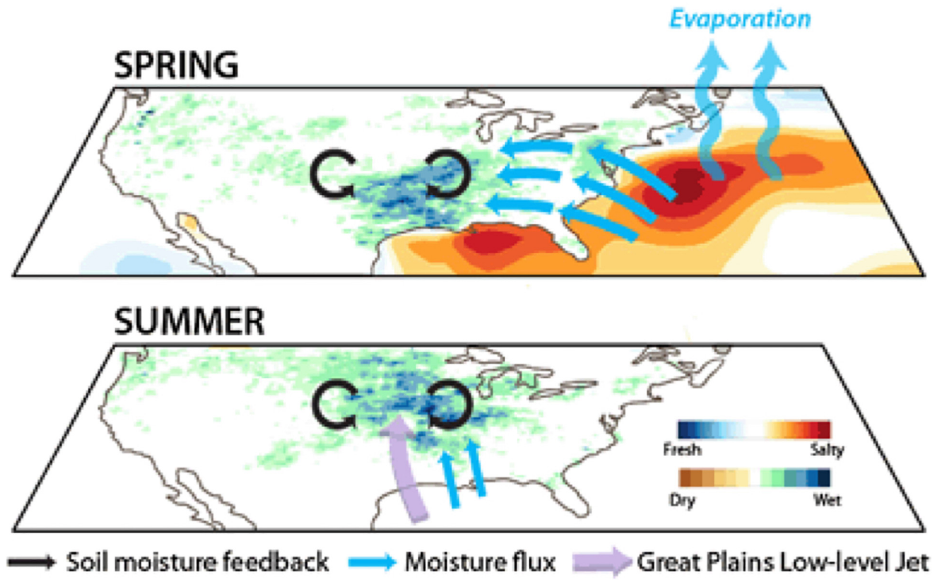

FIGURE 10 | Satellite SSS data improves prediction of land precipitation. Schematic figure illustrating the soil moisture mechanism bridging the 3-month time lag between springtime salinity anomalies and summer precipitation in the United States Midwest: in the western North Atlantic, higher springtime salinities are an indicator of enhanced moisture export onto the continental United States which converges in the South. This greatly increases soil moisture there, allowing for enhanced evaporation and leading to more atmospheric convection on land (upper panel). The intensified convection on land draws in more moisture from the Gulf of Mexico and leads to the enhancement of the Great Plains Low Level Jet, which carries moisture to the upper Midwest in summer (bottom panel). Adapted from Li et al. (2018), reproduced under Creative Commons license.

soil moisture content, and local land-atmosphere interaction (**Figure 10**) suggests that pre-season SSS is a physically meaningful predictor of the summer precipitation in the United States Midwest (Li et al., 2016a), winter precipitation in the southwestern United States (Liu et al., 2018), and monsoonal precipitation in the African Sahel (Li et al., 2016b). These studies found that SSS ranked as the most important predictor of land precipitation in those regions compared to ten other climate indices, including SST. We note that this linkage between terrestrial rainfall and subtropical SSS via the atmospheric moisture transport is another aspect of the land-sea linkages that is different from the direct land-sea linkage through river discharge as discussed in Section "Opening the Window to Better Understand Earth's Water Cycle."

Inferring Rainfall Over the Oceans

While more than 75% of precipitation occurs over the ocean, using satellite salinity as a direct rain gauge has proven challenging because both freshwater fluxes and ocean dynamics govern SSS variability (e.g., Vinogradova and Ponte, 2013a, 2017; Hasson et al., 2014; Yu, 2015; Guimbard et al., 2017). However, the window of opportunity may lie within a very short time period (typically 30 min) in tropical ocean regions where SSS freshening is strongly correlated with instantaneous rain rates similar in magnitude to those expected from earlier conceptual modeling studies (Boutin et al., 2016).

Despite recent advances, measurements of rain rate suffer from significant uncertainties and discrepancies, particularly within the ITCZ regions (Liu and Zipser, 2014). To reduce uncertainty, information on rain rate derived from satellite SSS sensors could provide an independent constraint over the ocean, where very few *in situ* rain rate measurements exist. Improving information on rain rates inferred from satellite L-band radiometry has two main challenges. One is related to difficulties in modeling the processes controlling the rain penetration into the upper ocean, keeping in mind that L-band radiometer signals penetrate only the upper few cm of the surface. Another challenge is constraining the physics of L-band radiometer measurements under rain conditions, including the characterization of the rain-induced surface roughness (e.g., Tang et al., 2013). In addition, reconciling point *in situ* observations or one-dimensional models with satellite observations needs to take into account the spatial heterogeneity of rain and SSS within a satellite pixel. The latter need could be addressed by taking advantage of the combination of multi-satellite information, such as SMOS and SMAP crossing points that are less than one hour apart (Supply et al., 2017), as well as measurements from synthetic aperture radar (SAR), rain radar, and other global precipitation mission (GPM) radiometers for characterizing the variability of rainfall, which is very intermittent.

Ocean Forecasting on the Horizon

Operational ocean forecasting systems, including those contributing to GODAE OceanView (Le Traon et al., 2015), assimilate ocean observations into high-resolution ocean models. Reanalyses and real-time forecasts produced by these systems are used to generate information about the past, current, and future ocean state, which is provided to downstream users. The quality of the information provided is dependent on the model and observations, and on the data assimilation system used to combine them. Unlike climate models, operational systems run close to real time, and thus the input streams need to be robust and timely, as well as be of good quality with known accuracy. To meet this need, sequential data assimilation (e.g., Carton et al., 2018) offers an alternative to the costly adjoint computations of climate-oriented ocean state estimates, ensuring computational efficiency of the operational ocean estimates and forecasts.

Although, at the moment, no ocean forecasting systems assimilate satellite SSS data operationally, there have been a number of efforts to develop schemes to do so by investigating the SSS data's impact on the ocean analyses and forecast. For example, as part of the ESA SMOS-NINO15 project, Martin et al. (2018) show how assimilation of satellite SSS data into the Met Office Forecasting Ocean Assimilation Model (FOAM) had a positive impact on the forecasting of tropical salinity changes, with an overall reduction in the root-mean-square (RMS) difference to Argo near-surface salinity data by 8%. These improvements in near-surface salinity also led to improvements in other modeled variables, including sea surface temperature and sea level. Positive impacts (a 5% RMS difference reduction) were also found in the Mercator-Ocean analysis and forecasting system, which was used to carry out a similar experiment during the 2015 ENSO event.

Another contributor to the GODAE OceanView program that aims to exploit satellite SSS data is NOAA's Real-Time Ocean Forecast System (RTOFS) for global and regional (United States west coast) applications. The project is at an early stage, with data streams from SMOS and SMAP incorporated into NOAA's environmental modeling data tank for model initialization and future assimilation. Ongoing test studies are encouraging, demonstrating improved representations of extremes of simulated sea-surface height anomalies, ocean surface density, mesoscale dynamics, and upper-ocean heat content), as well as better salinity constraints for downscaling to nested regional ocean/coastal models (Boukabara et al., 2016).

While recent results demonstrate the potential for operational assimilation of satellite SSS data (Toyoda et al., 2015), a number of issues need to be addressed prior to it becoming a reality. The bias correction of the satellite data relies on good quality *in situ* reference data, so improving the coverage of *in situ* SSS data should be a priority, especially in marginal seas, coastal regions, and high-latitude oceans. The timeliness (latency) of the data streams also needs to improve so that data are available for use within 24 h of measurement time, with the delivery of near real-time data being robust. Continuing improvement in the quality of the SSS retrievals and error/uncertainty information provided with the data will also feed into improved assimilation results.

OPPORTUNITY FOR INTEGRATION

As a newcomer, salinity remote sensing seamlessly integrated into the broader salinity network and global Earth observing system. Having global coverage with more uniform and finer spatio-temporal sampling, satellite SSS data complements sparser *in situ* salinity observations, filling in sampling gaps for regions with few *in situ* measurements such as in river plumes, coastal oceans, and marginal seas (**Figure 2**). Exploring how satellite SSS observations fit into a broad observing system in more detail, the following thoughts suggest a path for making satellite SSS data integration more meaningful.

Complementing the *in situ* Salinity Network

Ship observations, as well as measurements from drifters and moorings, tend to have high temporal resolution and accuracybut limited spatial coverage. Thus, satellite SSS measurements are useful for placing *in situ* observations in a broader context. Satellite SSS measurements are often used to interpret *in situ* observations during field experiments (e.g., Mahadevan et al., 2016), as well as to verify the presence of various ocean features that have large spatial scales, such as river plumes (Grodsky et al., 2014), eddies (Reul et al., 2014a), and ENSO signatures (Hasson et al., 2014).

In general, salinity data from satellite and Argo profiling floats are highly complementary: gridded satellite data have spatial resolutions as fine as a few tens of km on approximately weekly intervals, while the Argo array has a nominal sampling of one float per $3^\circ \times 3^\circ$ at 10-day intervals. Thus, combining the two datasets improves detection and characterization of mesoscale features, such as fronts and eddies that are not well captured by Argo alone (e.g., Grodsky et al., 2012; Reul et al., 2014a; Grodsky and Carton, 2018; Kao and Lagerloef, 2018) while mitigating the large-scale biases of satellite SSS. These synergistic products show particular improvement of salinity variability in regions where Argo floats are sparse (Toyoda et al., 2015; Lu et al., 2016) or regions with high variability such as that caused by ocean currents (Chakraborty et al., 2015). Moreover, satellite SSS alleviate the sparse sampling of *in situ* measurements in coastal oceans and marginal seas, thereby enhancing the capability to study land-sea linkages.

Prominent examples of the successful synergy between the satellite and *in situ* salinity observations are the NASA field campaigns Salinity Processes in the Upper-Ocean Regional Study, experiments 1 and 2, or SPURS-1 and SPURS-2, respectively (Lindstrom et al., 2015; SPURS-2 Planning Group, 2015). The SPURS program seeks better understanding of the global freshwater cycle through investigation of all the physical processes controlling the upper-ocean salinity balance. Set in ocean regions with evaporating (SPURS-1) and precipitating (SPURS-2) regimes, SPURS involves coordinated field work using moorings, autonomous instruments, ship-based process studies, remote sensing, and modeling. By combining large-scale Argo arrays with synoptic satellite images and local measurements from moorings, drifters, gliders, and microstructure profiling, the SPURS framework allows salinity variability to be observed across a range of scales, placing local and high-resolution salinity signals into a broader, mesoscale and basin-wide context.

Synergies With Other Satellite Measurements

In addition to complementing the *in situ* salinity network, satellite SSS has become an integral part of the globalspace-based Earth observing system, further enhancing a synergistic use of multi-variable satellite observations to address various Earth system science questions and applications.

Combined use of satellite SSS with other satellite measurements has enabled an array of new discoveries and capabilities, examples of which were highlighted above. Blended satellite and in-situ SSS (e.g., Melnichenko et al., 2014) enhanced the salinity monitoring capability. In particular, NOAA's Blended Analysis of Surface Salinity (Xie et al., 2014) based on Aquarius, SMOS, SMAP, and *in situ* salinities are produced operationally and used for monthly global ocean monitoring. Satellite SSS and SST together have made it possible to estimate surface density from space, facilitating the study of the surface water-mass formation processes (Sabia et al., 2015b) and linkages between the atmosphere and the deeper ocean. Combining SSS with altimetric measurements of sea surface height has allowed the quantification of eddy energy balance and to identify new features in mesoscale and large-scale oceanography. Combining satellite SSS, ocean currents, and precipitation has provided a powerful tool to study the effect of ocean circulation in mediating the ongoing changes in the hydrological cycle. The combined use of satellite SSS, soil moisture, precipitation, and ocean color data has helped identify the influence of riverine waters on ocean circulation.

Synthesis of satellite SSS and other ocean observations (both satellite and *in situ*) using ocean general circulation models in systems like ECCO help constrain the relatively uncertain estimates of freshwater exchange across the air-sea interface and produce multi-platform salinity estimates for climate research. As coupled assimilation capabilities advance in the coming decade, the value of satellite SSS to constrain air-sea and land-sea freshwater fluxes in coupled models will become even greater.

Complimentary by nature, physical-biogeochemical coupling provides another niche for satellite SSS integration opportunities. All carbon-related algorithms require contemporaneous information on SSS, SST, ocean color, and winds in order to estimate air-sea CO_2 flux, highlighting the need of satellite SSS in researching Earth's carbon. Promising results of such synergies were reported as part of the Pathfinders Ocean Acidification project and call for sustained and increasing research efforts in space-based biochemistry. In this regard, the ESA project OceanSODA aims to develop novel algorithms to advance the synergistic exploitation of satellite data for producing carbonate system parameters and to assess the potential impacts of these products on science, applications, and society.

Improving the Satellite SSS Error Budget for More Meaningful Integration

Reconciling and integrating information from various sources requires careful consideration of data uncertainties and errors. Traditionally, evaluation of satellite SSS data is performed through comparisons with *in situ* near-surface salinity measurements from ground-truth targets collected by Voluntary Observing Ships, Argo floats, tropical moorings, and ship-based CTD or thermosalinograph (TSG) measurements, as well as with gridded maps based on these *in situ* salinity measurements (Drucker and Riser, 2014; Tang et al., 2014, 2017; Boutin et al., 2016, 2018; Lee, 2016). Comparison against this ground-truth data provides a measure of satellite data biases and uncertainties.

In general, the differences between two salinity estimates from various sources (e.g., satellite vs. *in situ*) are attributed to two types of errors: observational errors and sampling errors. Sampling errors arise when one data type does not represent a process (or scale) that the other does[2], e.g., due to the differences in their spatial and/or temporal samplings. Sampling errors are the "expected" differences, the low bound at which two estimates are allowed to differ, and should not be confused with measurement errors. Thus, to interpret and understand the differences between datasets, it is crucial to separate those error sources. This is particularly important to assess whether a satellite dataset meets the mission accuracy requirement, by taking into account the sampling differences from *in situ* measurements that are considered ground truth.

Typically, observational errors for calibrated *in situ* salinity data are very small, on the order of ± 0.01 (e.g., Delcroix et al., 2005). For satellite SSS, observational errors are much larger primarily due to the relatively low signal to noise ratio, and to inaccuracies in satellite data calibration and SSS retrievals, ranging from imprecise modeling of the surface roughness impact, galactic radiation scattered by the sea surface, contamination by signals from land, rainfall, sea ice, sun, and radio frequency interference (RF), cold water sensitivities, and inaccuracies of ancillary data used in retrievals such as wind and SST (Le Vine et al., 2005, 2007; Font et al., 2010). For comparison, the accuracy for monthly satellite SSS at 100×100 km^2 is between 0.13 and 0.20, on average (Lagerloef et al., 2015; Tang et al., 2017; Boutin et al., 2018; Kao and Lagerloef, 2018).

Unlike the observational errors, sampling errors are couple-dependent (i.e., dependent on the two measurements being compared), and what is noise for one couple can be a non-issue for another. For example, satellite SSS retrievals represent the Gaussian-weighted average within the satellite footprint (40 km for SMOS and SMAP, and 150 km for Aquarius). In contrast, *in situ* measurements are pointwise observations. Thus, variability within a satellite pixel is smoothed in the satellite footprint, giving rise to a sampling error when compared with a point measurement (**Figure 11**). Sampling noise associated with sub-footprint variability can be a significant source of errors for *in situ* measurements in regions with strong transient dynamics, such as tropical regions influenced by rain bands, or regions affected by meandering currents and river plumes (Vinogradova and Ponte, 2013b; Boutin et al., 2016). While an issue in satellite/*in situ* comparisons, small-scale error is not a concern for comparing satellite and climate models with

[2]Other names have been also adopted in the community, with interchangeable use of "sampling" and "representation" errors; the latter is being more common in the modeling community. Observational errors have a variety of names, with most common being "measurement error," "instrument noise," "sensor noise," and "data accuracy."

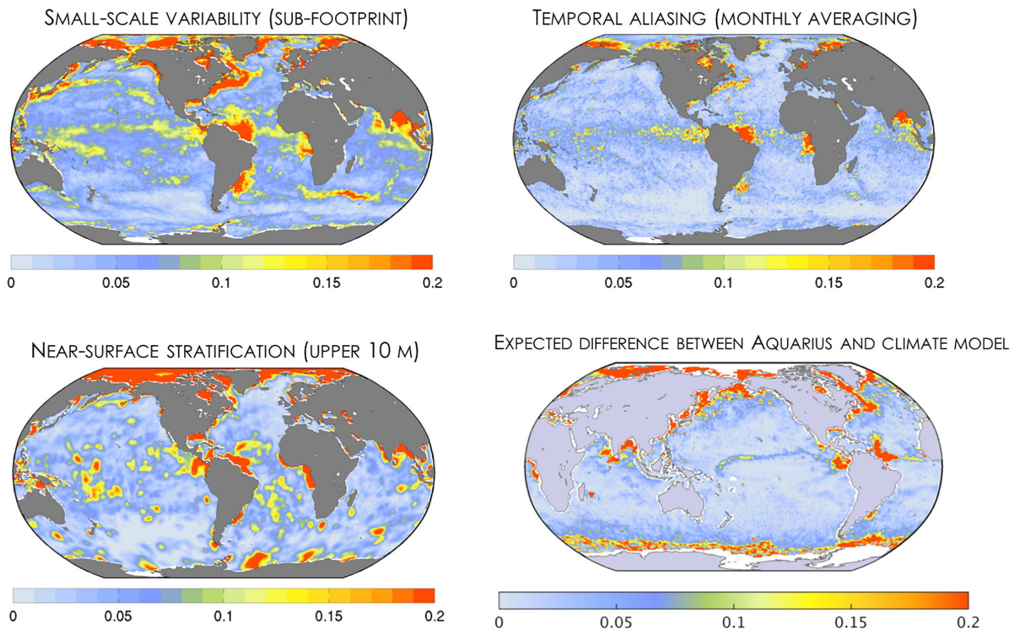

FIGURE 11 | Example of potential sampling errors associated with small-scale (sub-footprint) variability, temporal aliasing of satellite monthly fields, and salinity near-surface stratification in the upper ten meters. Total expected difference (as data error variance, in units pss^2) for the Aquarius SSS and a climate model. While small in the open ocean, sampling errors can be large in coastal regions and should be taken into account (removed) when estimating pure observational error for satellite salinity, as well as when reconciling (assimilating) it with other information. For example, such a correction can reach 0.7 pss near the Amazon, 0.5 pss in the Gulf Stream, and 0.4 pss in the Bay of Bengal. For details, see Vinogradova and Ponte (2012, 2013b) and Vinogradova et al. (2014).

similar horizontal resolutions of ∼1°. A potential concern for model/satellite comparisons is temporal aliasing of the satellite monthly fields (Vinogradova and Ponte, 2012). Models generally have high temporal resolution (an hour or less) and hence produce robust monthly mean average fields, unlike satellite SSS retrievals that have 3 to 7-day sampling intervals that can introduce aliasing errors when representing the true monthly averages (**Figure 11**).

With a few exceptions, both *in situ* and model pairings with satellite SSS will likely have representation errors associated with the sampling depth. While L-band satellites measure salinity in the top few cm of the ocean, the shallowest measurement depths for *in situ* sensors are typically 2 to 5 m (for most Argo floats) and 1 m for tropical moorings. Recent measurements of near-surface salinity structure show that there are situations where salinity stratification exists above 1 m, especially in the tropics where the effect of transient rain is important (Boutin et al., 2016; Drushka et al., 2016). The effect of near-surface stratification is summarized in a community paper by Boutin et al. (2016), providing the first step toward creating a systematic process of satellite SSS validation and performance assessments.

Until recently, sampling errors arising from sub-footprint variability, smoothing, and unresolved vertical gradients were not taken into account as they were assumed to be an order of magnitude smaller than the noise in satellite SSS. However, this is not the case in areas of high salinity variability. In order to improve the assessment of satellite SSS data and its integration with *in situ* measurements, it is necessary to better characterize the spatio-temporal distribution and decorrelation scales of the SSS variability at various scales. As an illustration, **Figure 11** shows the possible amplitudes of the known sources of sampling error for satellite, in situ, and model SSS estimates. These uncertainties are typically small in the open ocean, but could be significant regionally, particularly near the outflows of major rivers, western boundary currents, etc., and can reach one in extreme cases. If trying to estimate pure observational error for the satellite SSS retrievals by comparing it with in situ measurements, these sampling errors should be taken into account (removed). If the RMS difference between the satellite and in situ data is a measure of satellite SSS error, all sampling errors should be subtracted from the total RMS in a root-sum-square sense (assuming that all contributions are uncorrelated). While relatively small in the open ocean, such corrections can be significant. For example, using the values from Vinogradova and Ponte (2012, 2013b) and Vinogradova et al. (2014) and **Figure 11**, the sampling error correction can reach 0.7 in the vicinity of the Amazon river, 0.5 along the Gulf Stream, and 0.4 in the Bay of Bengal, indicating the importance of taking into account the sampling errors of pointwise in situ measurements in evaluating the uncertainties of satellite SSS.

In addition to comparing satellite SSS with *in situ* data and estimates from climate models, satellite-to-satellite comparisons open another route for evaluating data performance. Outside of the aforementioned regions with high sampling noise, the agreement between the satellite SSS data from different missions is remarkable (Boutin et al., 2018), allowing potential errors in *in situ* measurements to be identified (Tang et al., 2017). To facilitate this a potential way forward is to develop a common validation framework for multiple salinity satellites. Such a framework could include data from all L-band salinity satellites (SMOS, SMAP, and Aquarius), additional related datasets (precipitation, evaporation, and SST), databases of *in situ* salinity measurements for match-ups (Argo, TSG, moorings, and drifters), and inter-comparison reports at different spatio-temporal scales. On the horizon, ESA's Pilot Mission Exploitation Platform for Salinity project (Pi-MEP) aims to implement such a framework for SMOS salinity data. Similar efforts for SMAP and Aquarius in a potential partnership between ESA and NASA are under discussion.

Finally, another way to have more meaningful estimates of the satellite SSS error budget is to define appropriate metrics and indicators of data performance. The most commonly used quality indicators are the bias, the standard deviation, and the RMS differences between satellite and *in situ* salinities. These indicators enable a broad assessment of improvements or degradations of different versions of satellite products, provided that the reference *in situ* measurements and the spatio-temporal smoothing applied to the satellite measurements are the same. However, the details in how the data are processed and compared can affect the comparisons. For example, stringent filtering and data smoothing can potentially result in a very good standard deviation and RMS difference, while discarding the outliers that contain the true natural variability. Examples include eddies in river plumes (Akhil et al., 2016), small-scale salinity gradients relevant for advection studies (Hoareau et al., 2018), and others. Moving forward, it is desirable to expand the list of quality indicators that can provide information on the regional signal-to-noise ratios and the scales of variability detectable by satellite SSS measurements. For example, comparison of statistical distributions of SSS, could be effective for detecting outliers and quantifying extreme events (Supply et al., 2017; Olmedo et al., 2018), assuming sampling errors are properly addressed.

Complementary to the empirical approach to estimating the accuracy of satellite SSS, estimates of retrieval errors for satellite SSS from Aquarius have also been made available to users. The retrieval errors include the uncertainties related to factors such as instrument noise, ancillary data product uncertainties (e.g., wind and SST data to correct for surface roughness effect and thermal effects on brightness temperature measurements; Lagerloef et al., 2015), contamination near land and sea ice, and lack of sensitivity to salinity signals in cold waters (<5C, e.g., Meissner et al., 2018). Effort is also underway to obtain similar retrieval error estimates for SMAP SSS.

LOOKING AHEAD

Although progress in the satellite salinity observing system is commendable, its continued existence, maintenance, and innovation cannot be taken for granted. Drawing on the previous sections, we summarize the need for system continuity and enhancement, suggesting potential strategies for the upcoming decade and identifying potential stakeholders that could benefit from the uniqueness of satellite salinity products.

The Need for Continuity

Many of the science and application drivers discussed in Sections "Scientific Drivers for Satellite Salinity" and "Application Drivers for Satellite Salinity" require the continuity of satellite SSS. A longer record of satellite SSS will greatly benefit the understanding and prediction of interannual climate variability, including ENSO. In order to improve the robustness of a model's forecast skills, records of multiple realizations of interannual events are required, given the diversity of events such as the various flavors of ENSO.

Satellite SSS continuity is necessary to support longer-term monitoring and forecasting of synoptic extreme events, such as hurricanes and flooding. We have just scratched the surface of the ocean's salinity role in hurricanes, potentially bringing new approaches into the mix of tools necessary for tropical cyclone monitoring and forecasting. A way forward in hurricane forecasting is through improving the representation and coupling of physics in the underlying atmospheric and ocean models. Satellite SSS data, with its unique very-near surface as well as synoptic coverage, is key to understanding the exchange of heat across the air-sea boundary that fuels hurricane formation and evolution, particularly in regions that are influenced by strong freshwater input. Terrestrial floods, as another type of extreme event that impacts marine ecosystems, infrastructure, and economy, will also benefit from the continuity of satellite SSS data. This is especially the case because the continuity of satellite SSS is pivotal to monitoring the impacts of the changing water cycle on land-sea linkages. Newly developed techniques for monitoring and predicting extreme events using salinity are promising, but require continued measurements in order to be statistically robust.

Increasing statistical robustness through a longer satellite SSS record is also required to confirm new discoveries in mesoscale oceanography enabled by salinity remote sensing. A large and growing body of evidence suggests that temporal variability in eddy freshwater transports is particularly important and can be related to large-scale climate forcing. This interplay between scales is, however, poorly understood. Continuing satellite SSS observations at mesoscale resolution to accumulate a longer observational record is therefore critical to understanding these processes and scale interactions.

For operational oceanography, such as ocean and ecological forecasts, continuity of satellite SSS is key. There is little incentive from operational centers to exploit observations within an operational modeling framework without a sustained measurement system.

Moving toward decadal and longer observational coverage will clarify the role of salinity in the broader climate system and its linkages with the Earth hydrological and carbon cycles. As an interwoven component of ocean circulation and stratification, ocean biochemistry, and the global water budget, salinity is an important link connecting Earth's fundamental cycles. As the Earth's systems are undergoing dramatic transformations, long-term salinity trends will be another independent indicator of the Earth's health, now and in the future. Sustaining an accurate global satellite salinity observing system will make connecting the dots a reality. SSS is an essential climate and ocean variable of the GCOS. Recognizing the importance and advantages of satellite SSS, the 2016 GCOS Implementation Plan specifically recommended "Action 032: Ensure the continuity of space-based SSS measurements" (Belward et al., 2016).

The Need for Enhancement

Although it has been demonstrated that satellite SSS measurements improve many areas of science and applications much improvement in salinity remote sensing is still needed. The community recommends potential enhancements in three areas: accuracy, resolution, and coverage of satellite SSS.

Accuracy – Reducing Uncertainties

Despite their profound impact, salinity variations are rather subtle. Long-term trends in salinity are particularly subdued, ranging by 0.2 over multiple decades. In order to detect variations in salinity with high fidelity, including those variations associated with long-term climate changes, the accuracy of satellite SSS retrievals needs to be improved.

Similarly, accuracy must be improved to better resolve other ocean features of small magnitude, including eddies. With a typical eddy signal in SSS of 0.1–0.5 and an RMS error of satellite retrievals of a similar scale, the signal-to-noise ratio at mesoscale time and space scales is low. Therefore, to enhance the stability of the satellite SSS observing system SSS accuracy of less than 0.1 would be desirable. To achieve this goal, improvements in both retrieval algorithms and sensor technology are needed.

There is a sense of urgency to monitor high-latitude regions, making it imperative that salinity remote sensing reduces large uncertainties from satellite SSS data in cold waters, where retrievals are affected by reduced sensitivity of L-band brightness temperature and sea ice contamination. The unprecedented changes in sea ice melt, precipitation, and river runoff in the Arctic Ocean impact both geophysical and biochemical systems, including freshwater storage and export, ocean–ice–atmospheric interactions, primary production, and the ocean's response to acidification. Enhancing the accuracy of satellite SSS data over the Arctic will allow systematic monitoring of the changing Arctic SSS patterns and tracking of the pathways of freshwater as it enters the North Atlantic Ocean. Similar issues arise with large uncertainties of cold Antarctic waters, affecting our ability to accurately document the variability of the Subantarctic Front and Polar Front zones, along with the related water-mass formation processes that affect global overturning rates. To monitor the ongoing changes in the polar oceans, technology development that addresses the current capability gap in a cost-effective way is necessary.

Resolution – Monitoring Mesoscale Features

While current satellite missions have substantially advanced our understanding of variations in SSS, a significant part of the ocean variability associated with mesoscale and submesoscale processes is still missing. In practice, resolving ocean features requires capturing the scale of the so-called Rossby radius of deformation – a length scale at which ocean currents feel the effects of the Earth's rotation. In the ocean, the Rossby radius varies geographically, ranging from 200 km near the equator to 10–20 km in high latitudes (Chelton et al., 1998). The SSS measurements from the currently operating satellite missions SMOS and SMAP have spatial resolutions of approximately 40 km, which means that they only resolve the Rossby radius (and ocean eddies) up to 30° away from the equator. Therefore, it is advantageous to increase the spatial resolution of satellite SSS to better resolve mesoscale variability and to measure closer to the coasts to further enhance the studies of land-sea linkages.

Recent studies elevated the role of ocean submesoscale currents O(1–10 km), demonstrating their key contribution to the Earth energy budget and marine biogeochemistry (e.g., Su et al., 2018). However, measuring submesoscale SSS from space is beyond the current capability of L-band satellite remote sensing. Significant technology innovation is underway with the SMOS High Resolution (SMOS-HR) concept currently studied at CNES that can potentially provide 10-km resolution data during the coming decade.

Coverage – Better Sampling of Coastal Oceans

Better satellite coverage is needed near the continental margins, including near major river plumes that have implications for hydrological cycle closure. Although current salinity missions provide SSS data as close as 40 km to the coast, land contamination remains a concern, with uncertainties exceeding 1 within 100 km distance from the coast. With growing scientific and public interest in SSS data near the coasts, it is becoming critical to resolve coastal processes, including land-sea exchange, hydrological and biochemical cycles, coastal upwelling, freshening, pollution, and other processes that impact biology, the ecosystem, and human health.

Overall Strategy for Next Decade

Because salinity is an essential ocean and climate variable, the future of salinity observations impacts the success of the Global Ocean Observing System, including the network of Earth observing satellites. Given the network's integrated nature, future satellite SSS missions will benefit from a synergistic approach to the observing system that will target critical components of the Earth system, including ocean circulation, air-sea exchanges, the hydrological cycle, and biogeochemistry. The longevity of the satellite SSS observing network relies on both technological developments and strong partnerships, driven by the common goal of advancing science and applications for societal benefit.

Strategy for Technological Innovations – Simultaneous Measurements by Multiband Radiometers

The science and application drivers, together with the challenges ahead, set specific requirements for the coming decades for satellite SSS in order to better support end-users. With a synergistic observing system in mind, one requirement is to monitor SSS at 25-km spatial resolution or less, which is the resolution of current SST and wind measurements made by passive microwave radiometers, and with global coverage at least every 3 days. Coincident measurements of SST and wind greatly facilitate SSS retrieval because, as Section "Introduction: Remote Sensing of Salty Oceans" notes, SST and wind are needed as ancillary data in SSS retrievals. The possibility of simultaneous measurements of SSS, SST, and winds is especially relevant for the tropical, low-latitude regions, where existing satellite SSS measurements are most accurate. The concept of multifrequency radiometers is being explored, specifically those covering a combination of P-, L-, C-, and/or X-bands. As all geophysical parameters can be measured at multiple microwave frequency bands, multiband microwave radiometers will be able to combine data retrieved from several bands in order to achieve improved and simultaneous measurements.

In order to enable remote sensing of SSS in cold water around the polar regions, concepts involving P-band radiometers are being considered. It has been recognized since the 1970s that the optimal radio frequency for salinity remote sensing is between 500 and 800 MHz (Wood et al., 1975; Swift and Mcintosh, 1983; Kendall et al., 1985). At these frequencies, the sensitivity to salinity is nearly invariant with water temperature and is up to 3 times more sensitive than at L-band for water temperatures less than 10°C. However, the first missions were formulated with radiometers that operated in the protected Earth Exploration Satellite Service (EESS) spectrum from 1.4 to 1.427 GHz for passive radiometry use due to concerns of radio-frequency interference (RFI) (Kerr et al., 2001; Lagerloef et al., 2008; Entekhabi et al., 2010; Oliva et al., 2016). Recently, microwave radiometer technology has evolved to filter RFI and extract clean signals if present, expanding the potential spectrum of operation (Ruf et al., 2006; Misra et al., 2013, 2018; Piepmeier et al., 2014). Radiometers with the ability to measure the spectrum in the range of 0.8–3 GHz can give the same benefit of simultaneous wind and SST retrieval, and significantly improve salinity measurements in general and in cold water in particular.

Such a system would also have applications for the cryosphere and the polar oceans (Lee et al., 2016). Current radar measurements of sea ice thickness have relatively large uncertainties, particularly for thin sea ice of less than 1 m; the combined multi-frequency (P-/L-band) radiometry also aims to fill a capability gap in measuring the thickness of seasonal sea ice. Improvement of sea ice thickness measurements and SSS in marginal ice zones are important to ocean-ice interaction studies and seasonal ice forecasts, as well as sub-seasonal/seasonal weather forecasts. Additionally, L/P-band radiometry has the capability to measure ice-shelf temperature, which has important implications for sea level research.

The challenge of a multi-band approach is the trade-off between the cost and the resolution of the satellite retrievals, which requires further analysis.

Building Partnerships – Exploring International, Domestic, and Commercial Spaces

International collaboration is important to ensure the consistency of satellite SSS across different missions, as well as mission continuity supporting research and applications. With both SMOS and SMAP in orbit, there is a need for collaboration on validation platforms and cross-calibration between the two satellites' SSS measurements.

In addition to cross-calibration, a platform that enables consistent validation and merging of multi-satellite SSS measurements is needed. Such capabilities are being explored within ESA's Pi-MEP framework and Climate Change Initiative project, as well as in NASA's MEaSUREs (Making Earth System Data Records for Use in Research Environments) programs. Through close collaboration, ESA and NASA salinity teams need to perform an inter-comparison of the various algorithms and ancillary

TABLE 1 | Summary of recommendations for salinity remote sensing for next decade.

RECOMMENDATION	
(1) CONTINUITY	Ensure the continuity of space-based salinity measurements to support the scientific and operational drivers such as the monitoring of longer-term changes of the ocean's large-scale and mesoscale variability and the relationship with climate variability, characterizing land–ocean interactions and oceanic linkages with hydrological and biogeochemical cycles, constraining ocean state estimates, supporting operational oceanography, and improving forecasting of extreme events and their impacts (e.g., floods and droughts).
(2) ENHANCEMENT	Enhance satellite SSS observing system to improve accuracy, resolution, and coverage in order to better support the aforementioned scientific and operational applications. In particular, it is important to improve satellite SSS accuracy in polar oceans through technological innovations and better retrievals. At a minimum, future satellite missions should have accuracy, resolution, and coverage that are no worse than what have been demonstrated with the previous and existing missions.
(3) INTEGRATION	Advance the integration of satellite SSS into global ocean observing network and modeling/assimilation. Improve the understanding of satellite SSS uncertainties by characterizing satellite SSS measurement errors, the effect of sampling differences from the ground-truth in-situ salinity observations, and the underlying physical processes that contribute to the effects of the sampling differences. Improving the understanding of satellite SSS uncertainties and the effects of sampling differences from *in situ* measurements are critical to the synthesis of satellite SSS from different missions to produce climate data record, to synthesize satellite SSS with *in situ* salinity measurements (e.g., blended products), and to integrate satellite SSS with other satellite and *in situ* measurements effectively through data assimilation.
(4) INNOVATION	Develop innovative, cost-effective solutions to meet continuity and enhancement requirements for future satellite SSS observing system. Explore multi-frequency instrument concept to enable simultaneous measurements of various parameters (e.g., sea surface salinity, sea surface temperature, ocean surface winds, sea ice properties) to better support the aforementioned scientific and operational drivers.
(5) PARTNERSHIP	Pursue international collaborations to support the continuity, enhancement, integration, and innovations for satellite SSS observing system. The collaborations include technology and cost sharing, consistent model function for satellite SSS retrievals, and common framework for satellite SSS calibration and validation.

datasets employed in the SSS retrievals of each satellite mission. Choosing a common set of ancillary parameters and models, as well as refining methods used for characterizing SSS uncertainties will provide consistent information on the characteristics of retrieved SSS, particularly in regard to uncertainty, allowing the development of more accurate, merged SSS products that address the requirements expressed by end-users and the science community.

In summary (see also **Table 1**), a way forward to continue and enhance salinity remote sensing as part of the integrated Earth Observing System addressing societal needs is by implementing innovative solutions and synergistic measurement concepts, by leveraging current technological advances, by coordinating with international partners to ensure complementary capabilities, and by taking advantage of emerging capabilities in the commercial sector to lower the cost of making research-quality Earth observations.

AUTHOR CONTRIBUTIONS

NV and TL developed the conception of the review. All authors wrote the parts of various sections of the manuscript and contributed to the manuscript revision, read, and approved the submitted version.

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Scaling Up From Regional Case Studies to a Global Harmful Algal Bloom Observing System

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Harmful algal blooms (HABs) produce local impacts in nearly all freshwater and marine systems. They are a problem that occurs globally requiring an integrated and coordinated scientific understanding, leading to regional responses and solutions. Given that these natural phenomena will never be completely eliminated, an improved scientific understanding of HAB dynamics coupled with monitoring and ocean observations, facilitates new prediction and prevention strategies. Regional efforts are underway worldwide to create state-of-the-art HAB monitoring and forecasting tools, vulnerability assessments, and observing networks. In the United States, these include Alaska, Pacific Northwest, California, Gulf of Mexico, Gulf of Maine, Great Lakes, and the United States Caribbean islands. This paper examines several regional programs in the United States, European Union, and Asia and concludes that there is no one-size-fits-all approach. At the same time, successful programs require strong coordination with stakeholders and institutional sustainability to maintain and reinforce them with new automating technologies, wherever possible, ensuring integration of modeling efforts with multiple regional to national programs. Recommendations for scaling up to a global observing system for HABs can be summarized as follows: (1) advance and improve cost-effective and sustainable HAB forecast systems that address the HAB-risk warning requirements of key end-users at global and regional levels; (2) design programs that leverage and expand regional HAB observing systems to evaluate emerging technologies for Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) in order to support interregional technology comparisons and regional networks of observing capabilities; (3) fill the essential need for sustained, preferably automated, near real-time information from nearshore and offshore sites situated in HAB transport pathways to provide improved, advanced HAB warnings; (4) merge ecological knowledge and models with existing Earth System Modeling Frameworks to enhance end-to-end capabilities in forecasting and scenario-building; (5) provide seasonal to decadal forecasts to allow governments to plan, adapt to a changing marine environment, and ensure coastal industries are supported and sustained in the years ahead; and (6) support implementation of the recent calls for action by the United Nations Decade 2010 Sustainable Development Goals (SDGs) to develop indicators that are relevant to an effective and global HAB early warning system.

Keywords: biodiversity, phytoplankton, biotoxin, phycotoxin, ecological forecasting, early warning system, stakeholder engagement, earth system science

INTRODUCTION

Commonly known in many parts of the world as floraciones algales nocivas (FANs), prolifération d'algues nuisibles (PANs), or harmful algal blooms (HABs), potentially noxious algae growth in coastal environments worldwide is characterized by appearing without warning and often lingering long past expectation (see **Supplementary Table S1** for a list of abbreviations in **Supplementary Material**). The number of different micro- and even macro-algae responsible for causing HABs is remarkable, which adds to the difficulty in identifying universal causes and mechanisms driving both the initiation and termination of HABs in marine and freshwater environments. Complete prevention or mitigation of HABs may never be realistically achieved given the complex ecology typical of this broad collective that includes plant-like organisms and cyanobacteria. When human pollution or activities are a known cause or contributing pressure (Anderson et al., 2002), however, preventive measures may be possible (Anderson et al., 2015). For example, the regulation of human-derived nutrient inputs can benefit areas where HABs are prevalent (e.g., Ehlers, 1994; Glibert and Burford, 2017). International regulations also prevent contaminated ballast water exchange in sensitive marine regions and aim to diminish transport of organisms across regions (International Maritime Organization [IMO], 2003; Burkholder et al., 2007). For most scientists and policy-makers engaged in the HAB problem, however, the focus has shifted from prevention to mitigation and adaptation through frequent monitoring of causative organisms and their toxins using innovative technologies, short-term prediction, and strong stakeholder participation that alleviates the strain on ecosystems, public health, and local-to-regional economies and reduces the exposure to humans and wildlife (Anderson, 2009).

There is also a growing recognition that the increase in global mariculture and aquaculture, necessary for protein food supply to humanity, is bringing the potential risk of HABs into focus (Anderson, 2009). Declining wild fish stocks are creating a need for more efficient farm production methods. Indeed, a central theme of the European Commission (EC) Common Fisheries Policy is to improve aquaculture outputs. HAB toxins can contaminate farmed finfish and shellfish stocks, just as they do wild populations, leading to a heightened risk of seafood-borne illnesses when consumed by humans, with subsequent regulatory closures of recreational and commercial harvest. Aquaculture facilities also experience hypoxic events from high-biomass algal blooms that lead to high mortality of enclosed finfish. Shellfish production volumes have seen many peaks and troughs over the past 30 years, with declines potentially coinciding with HAB events accompanied by prolonged shellfish growing area closures (e.g., Cusack et al., 2016). The latest available European bivalve shellfish aquaculture production figures show a yield of 612,579 tons in 2016 with an estimated value of 1,111 million USD (Fisheries and Aquaculture Information and Statistics Branch - 02/08/2018)[1]. With this increased dependence on aquaculture comes significant food safety concerns. The focus on food quality (e.g., through food hygiene legislation to guarantee safe food) is acknowledged by industries who capitalize on the perception that seafood is very safe due to the high-quality regulations in place and use this as a marketing tool for their products. Seafood consumers often judge HAB disruptions as a signal of unreliability and look to industry competitors for future product supply. While fishery closures and recalls from HAB disruptions protect consumers, they also tend to be reactive since the timing of HAB and biotoxin events is often unpredictable days to weeks in advance. An effective HAB warning system should have components that are tailored to aquaculture to allow producers to change their husbandry practices, such as avoiding the handling of shellfish, proactively relocating stocks, harvesting shellfish earlier or canceling a delivery in order to minimize losses and waste due to contaminated stock, or, by intensifying harvest prior to a HAB event.

Harmful algal bloom risk can be difficult to quantify because HABs are characterized by an extremely diverse set of processes and impacts, all with significant societal relevance that warrants a decisive and strategic response from the ocean observing community. International co-operative research has proven decisive in identifying and institutionalizing tools to improve the understanding of HAB dynamics and design mitigation strategies. Indeed, the international programs GEOHAB (2000–2013) and GlobalHAB (established in 2016 to run until 2025[2]), both sponsored by SCOR (Scientific

[1] www.fao.org
[2] www.globalhab.info

Committee on Oceanic Research) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) foster research on HABs across ecosystems that share common features, comparing key species involved and the oceanographic processes that influence their population dynamics (GEOHAB, 2001, 2005, 2006, 2008, 2010a,b; Kudela et al., 2017). Under GEOHAB and GlobalHAB, the international community defined priority goals, objectives, and scientific road maps that constitute the basis for HAB research and management at local and regional scales. Importantly, these programs also interface with other trans-national and international efforts such as the Global Ocean Observing System (GOOS), Group on Earth Observations Biodiversity Observation Network (GEO BON), Marine Biodiversity Observation Network (MBON), and GEO/Blue Planet to implement HAB-specific efforts within these coordinated networks.

With the adoption of the UN list of Sustainable Development Goals (SDGs) as a global rubric for structuring future applied science objectives (G7, 2018. Paris Accord), the mandate for sustained ocean observing systems is crystallizing around these 17 central themes of societal benefit. For ocean observing systems with HAB monitoring programs, there is a pre-existing culture of focusing science outcomes and decision-making products around a set of well-defined stakeholder requirements. In other words, the monitoring of HABs and their toxins has fundamentally been a science-driven activity but with strong application to private industry, management, and policy decisions. The ocean observing community now recognizes the transcendent role that HAB monitoring plays in bridging ocean observing to ocean policy and to the many overlapping indicators specified by the SDGs. These targets and indicators fall within the themes of food security (SDG 2), human health (SDG 3), water supply (SDG 6), sustainability (SDG 11), climate change (SDG 13), and aquatic ecosystems (SDG 14). HABs impact each of these sectors: food security via contamination of seafood or direct mortality of fish stocks, human health via seafood contamination, water contamination, and reduction in air quality, water supply via poisoning of drinking reservoirs and general degradation of water quality, our ability to sustain resilient coasts, climate-related hazards in the aquatic zone, and the overall functioning and services that aquatic ecosystems provide. Improvement in seafood production also supports recommendations from the United Nations Environment Program (UNEP), which has voiced concerns that as the global population increases toward a predicted 9.1 billion people by 2050, the western preference for diets rich in meat and dairy products is unsustainable. Additionally, when it comes to food and economic security, marine aquaculture is vital to regional micro-economies as well as national economies.

This contribution aims to illustrate a variety of regional solutions to HAB observation and prediction as they fit within the context of the global problem. The paper does not attempt a comprehensive literature review on global HABs (c.f. Glibert et al., 2018) and does not purport to cover all the important matters pertinent to this vast and complicated subject, e.g., *in situ* bloom-prevention strategies (cf. Anderson et al., 2015, 2017). A common theme across regional observing systems is the engagement with relevant stakeholders and policy makers. Stakeholder outreach, in this context, does not simply refer to rudimentary display of summary data and analysis, but rather a tight feedback loop that generates iterative improvements on data and products and innovative communication strategies for impactful decision-making. The regional perspectives provided below demonstrate the utility of state-of-the-art, real-time observational capabilities, predictive models, and citizen science for meaningful academic-private-government partnerships that benefit society and are often tailored to a specific stakeholder audience. Moreover, our intent is not to document all HAB monitoring programs globally (c.f. Anderson et al., 2001), but rather to highlight key examples to identify commonalities and best practices. First, the paper highlights some key regional partnerships in the United States that enable effective HAB monitoring, followed by an overview of HAB monitoring and forecasting programs in the EU and Asia. The paper closes with a summary of lessons learned and future directions for integrating HAB monitoring and prediction into a global ocean observing framework.

REGIONAL CASE STUDIES

The United States Integrated Ocean Observing System (U.S. IOOS)

Ocean observing systems have been a proposed solution to long-term, sustained HAB monitoring for several decades (Anderson, 2008; Babin et al., 2008; Jochens et al., 2010; Anderson et al., 2012). In collaboration with many federal agencies - the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration offices, such as United States IOOS, the National Centers for Coastal Ocean Science (NCCOS), and Ocean and Atmospheric Research (OAR) – are funding regional programs in the United States that support HAB monitoring programs as part of a broader network of ocean observing in Alaska, the Pacific Northwest, California, Gulf of Mexico, Atlantic Northeast, Great Lakes, and the United States Caribbean islands. A major component driving the success of transitioning these HAB monitoring and forecasting tools from research to operations is the role that the IOOS Regional Associations play in transferring knowledge from academic, tribal, and industry partners to routine and sustained operations within the United States IOOS enterprise, often in partnership with state agencies. This section highlights many IOOS-funded activities but does not cover all regional programs and funding agencies in the United States that deal with HABs. Two important themes that emerge from the United States IOOS case studies are first, that each region has developed HAB programs that work well for that region–there is no single United States HAB observing system. Second, with few exceptions, these HAB monitoring and forecasting efforts are a part of the larger Ocean Observing framework, leveraging infrastructure, data, and personnel, and public benefit by addressing HABs as one of many important coastal ocean issues.

Alaska

Harmful algal blooms have been documented in coastal Alaska since the late 1700s, including those that can cause paralytic shellfish poisoning (PSP). Despite the risks of PSP, coastal Alaskans have always depended on wild shellfish for subsistence and recreational seafood harvests. The state currently tests only commercial shellfish products in Alaska using the mouse bioassay, but there is no routine state testing of non-commercial harvests. The Southeast Alaska Tribal Ocean Research (SEATOR) uses the receptor binding assay to determine paralytic shellfish toxins (PSTs) in shellfish tissue for subsistence harvesters. PSTs are considered unsafe by the U.S. Federal Department of Agriculture (FDA) if above the regulatory limit of 80 μg per 100 g of tissue. To reduce risk to subsistence and recreational shellfish harvesters, a number of regional monitoring programs have emerged to provide HAB-related information to harvesters. In 2017, representatives from these groups joined with research institutions and state and federal agencies in 2017 to form the Alaska Harmful Algal Bloom Network (AHAB). The goal of AHAB is to provide a statewide approach to HAB awareness, research, monitoring and response in Alaska.

The SEATOR is a consortium of 16 Tribal governments in southeast and southcentral Alaska, as well as academic, governmental, and non-profit partners. The SEATOR cornerstone partnership formed around the increasing threats of HABs and PSP in order to reduce the risks to traditional harvesters and increase year-round access to safe, wild shellfish. SEATOR partners monitor one or more community harvesting sites weekly by collecting and analyzing phytoplankton samples, filtering water samples to test for particulate toxins, and shipping bi-weekly shellfish samples to the Sitka Tribe of Alaska's Environmental Research Lab for PSP toxin analysis using the Receptor Binding Assay (RBC, AOAC Method 2011.27). Shellfish toxicity results are sent to partners, state regulators, and researchers immediately after testing. Any shellfish with toxin levels above the FDA's regulatory limit trigger public service announcements on local media stations and on SEATOR web pages. With weekly "eyes on the water" and shellfish results within 48 h of collection, SEATOR partners can establish subsistence management plans, reduce the risks to their citizens, and increase participation in traditional shellfish harvesting. All SEATOR data are made publicly available on the SEATOR website[3] and the AHAB network site hosted by the Alaska Ocean Observing System (AOOS) and are used by resource managers and subsistence harvesters. The SEATOR partnership's success suggests that while Alaska's long coastlines and dispersed populations provide unique challenges for effective HAB and PSP monitoring, community-based sampling combined with close, regional partnerships can offer an effective way to reduce the human health risks from HABs.

While the SEATOR partnership was initially only focused on PSP-risk mitigation, partners' weekly phytoplankton and environmental observations have allowed the group to respond to emerging HAB threats in Alaska as well. SEATOR partners have observed blooms of *Pseudo-nitzschia*, the phytoplankton responsible for Amnesic Shellfish Poisoning (ASP), more than 30 times since the group's formation. When high *Pseudo-nitzschia* concentrations are observed, the Environmental Research Lab is able to test water and shellfish samples for domoic acid (DA) in addition to PSP toxins using an enzyme-linked immunosorbent assay (ELISA). Luckily, DA has not yet been detected at levels threatening to human health, although it has been detected in marine mammals (Lefebvre et al., 2016), highlighting the potential for future impacts. Given the pervasiveness of DA toxicity in Washington and Oregon and the high participation rates in traditional shellfish harvesting in Southeast Alaska, the SEATOR partnership's proactive monitoring approach to an emerging toxin is warranted.

With Alaska's extensive coastline and a significant population of subsistence users, expanding capacity for HABs sampling, testing and event response is imperative. Alaska is already seeing the benefits from collaborative efforts through the Alaska HAB Network, as well as technology transfer and lessons learned from other regions.

Pacific Northwest

The Pacific Northwest has a long history of human interaction with HABs as passed down through Native American oral history (Horner et al., 1997). The first recorded incident was four illnesses and one death among Capt. George Vancouver's HMS Discovery crew in 1793 likely from PSP after eating shellfish in what is now British Columbia, Canada waters (Quale, 1966; Kao, 1993; Lewitus et al., 2012). Reported deaths from PSP occurred in Washington in 1942 and in Oregon in 1933 (Lewitus et al., 2012). Today, the most concerning HAB for human health and the regional economy is the threat of PSP from *Alexandrium*, Diarrhetic Shellfish Poisoning (DSP) from *Dinophysis,* and ASP from *Pseudo-nitzschia*. Blooms of *Alexandrium* and *Dinophysis* primarily occur in the inland coastal waters of Puget Sound, whereas blooms of *Pseudo-nitzschia* typically occur on the outer Washington-Oregon coast (Moore et al., 2009; Trainer et al., 2009a,b, Trainer et al., 2013; Lewitus et al., 2012). A combination of monitoring approaches, including state-funded programs, citizen science programs and advanced, automated technology such as the Environmental Sample Processor (ESP), as well as forecasts are used to provide early warning of impending HABs.

State monitoring of both recreationally and commercially harvested shellfish for marine biotoxins began in Washington in the 1950s (Nishitani and Chew, 1988). Since then, PSP shellfish toxicity has increased in frequency, magnitude, and geographic scope, and shellfish harvesting closures are now a regular occurrence in almost all of Puget Sound (Rensel, 1993; Trainer et al., 2003; Lewitus et al., 2012). Harvest closures related to ASP first occurred during 1991 and were widespread throughout Washington, Oregon, and northern California (Wekell et al., 1994). *Pseudo-nitzschia* blooms have warranted numerous subsequent closures along the coast and associated estuaries, some lasting for over one year (Trainer et al., 2012). In contrast to PSP, only a few ASP closures have occurred in Puget Sound (Trainer et al., 2003). The first documented cases of DSP in the Pacific Northwest (and the United States, for that matter), occurred more recently in 2011 when three people fell

[3]http://www.seator.org/

ill after consuming mussels they harvested locally in Sequim Bay, Washington (Trainer et al., 2013).

The first line of defense to protect local communities from the threat of various HABs in Puget Sound is provided by a citizen science monitoring program called SoundToxins[4]. SoundToxins is a partnership of shellfish growers, fish farmers, Native American tribes, environmental learning centers, local health jurisdictions, colleges, and volunteers. Participants are provided equipment and training to collect water samples and identify key HAB species, including *Alexandrium*, *Pseudo-nitzschia*, *Dinophysis*, and *Heterosigma*, at 28 locations near their growing areas or near their homes. The information is entered into a centralized database that alerts the Washington State Department of Health to sites where HAB species are identified and/or where their abundance is increasing so that they can identify and prioritize additional shellfish toxin analyses.

On the outer Washington coast, coordinated monitoring at six beaches by the Olympic Region Harmful Algal Blooms (ORHAB) program provides early warning of HABs of *Pseudo-nitzschia* (Trainer and Suddleson, 2005). ORHAB is a partnership of academic, federal, tribal, and state researchers and managers. The program was initially funded for 5 years by the National Oceanic and Atmospheric Administration (NOAA) Monitoring and Event Response to Harmful Algal Blooms (MERHAB) program but was successfully transitioned to an operational monitoring program funded by Washington State through a surcharge on recreational shell fishing licenses. The ORHAB program uses a simple combination of monitoring the abundance and toxicity of *Pseudo-nitzschia*; when cell concentrations exceed a size-dependent threshold (30,000 cells per L for large cells and 1 million cells per L for small cells), toxin testing of seawater particulates (e.g., filtered phytoplankton cells) is conducted. Like SoundToxins, the Washington State Department of Health uses ORHAB data to identify and prioritize additional shellfish samples for toxin analysis.

Beach monitoring does not determine whether a toxic bloom of *Pseudo-nitzschia* is lurking just off the coast. This is because ORHAB sampling is conducted at beaches, while the primary sources of toxic cells are offshore retentive oceanographic features, such as the seasonal Juan de Fuca eddy located off the Juan de Fuca Strait of the northern Washington coast (Trainer et al., 2009a). Retentive circulation, relatively low grazing rates compared to growth rates, and both macro- and micro-nutrient stress can contribute to the abundance and toxicity of *Pseudo-nitzschia* in the Juan de Fuca eddy, making it an initiation site for toxic HABs (Olson et al., 2008; Trainer et al., 2009a,b; MacFayden and Hickey, 2010). Toxic cells can escape from the eddy and be transported to the Washington coast during storm events when downwelling-favorable winds drive onshore flow (**Figure 1**). Immediately to the south-southeast of the Juan de Fuca eddy is the Northwest Enhanced Moored Observatory (NEMO), a real-time mooring system that is

[4]www.soundtoxins.org

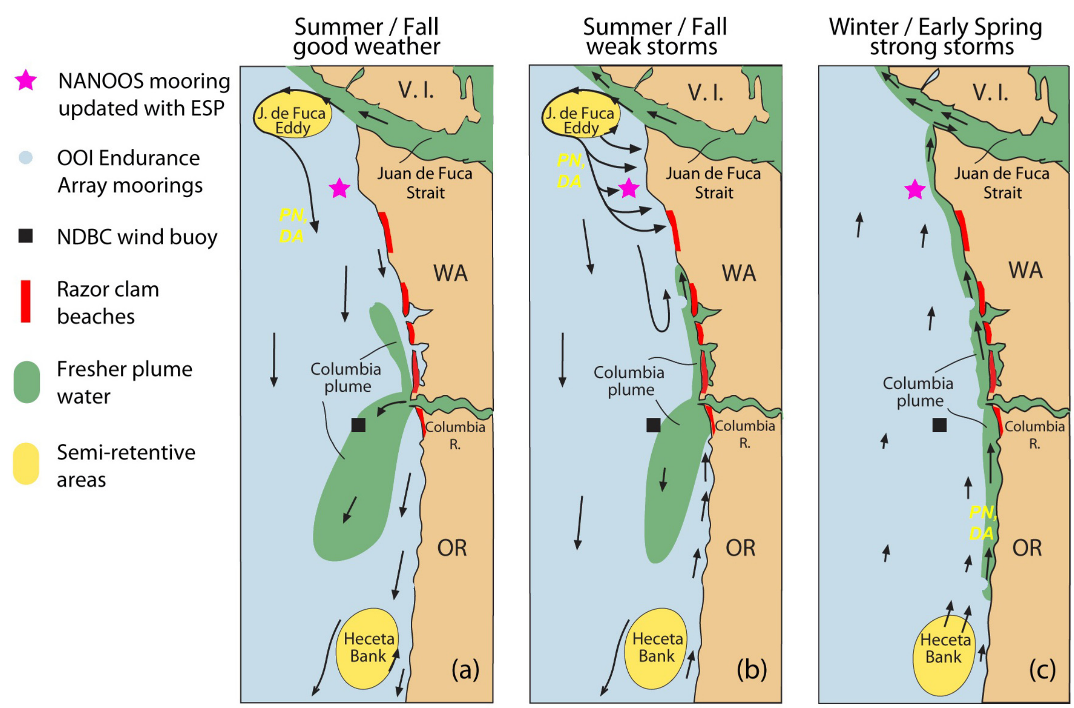


FIGURE 1 | Schematic diagram of the outer Washington coast showing the locations of semi-retentive oceanographic features that are known to be HAB initiation sites (i.e., the Juan de Fuca eddy and Heceta Bank), ocean observing platforms, razor clamming beaches, and the transport pathways during **(a)** summer/fall good weather, **(b)** summer/fall weak storms, and **(c)** winter/early spring strong storms. *PN* and *DA* are *Pseudo-nitzschia* and domoic acid, respectively, and indicate the pathways that toxic HABs can take from HAB initiation sites to coastal beaches. Figure modified from Hickey et al. (2013).

owned and operated by the University of Washington and the Northwest Association of Networked Ocean Observing Systems (NANOOS). In 2016, with funding from the NOAA IOOS Ocean Technology Transfer program, NEMO was enhanced with an advanced, remote, autonomous, near real-time HAB biosensor called the Environmental Sample Processor (ESP). The ESP uses sensitive and specific molecular assays to quantitatively detect *Pseudo-nitzschia* and domoic acid (DA) using sandwich hybridization assay and competitive enzyme-linked immunosorbent assay, respectively (Doucette et al., 2009; Scholin et al., 2009). The results of the assays are captured in a photograph that is relayed via telemetry in near real-time. The entire process, from sample collection through results delivery, takes as little as 3 h. The ESP is deployed on NEMO during high risk seasons when blooms could interfere with shellfish harvest (i.e., spring and fall). The data from the ESP are served by the NANOOS Data Visualization System (NVS) and the "Real-time HABs" application[5] that NANOOS developed. This website incorporates contextual data and other data products to enhance interpretation and understanding of the ESP data (e.g., 1–3-day advection forecasts illustrating horizontal water transport calculated from current meter data) by state and tribal resource managers and other interested parties.

When available, near real-time ESP observations of *Pseudo-nitzschia* and DA inform a forecast product called the Pacific Northwest HAB Bulletin that currently is being transitioned from a research- to an operational product. Once operational, the most current PNW HAB Bulletin will be distributed to managers and other partners on the NANOOS website where archived Bulletins now can be viewed[6]. This product was originally developed through a partnership among NOAA Northwest Fisheries Science Center, the University of Washington, and the Centers for Disease Control and has since been funded by the NOAA MERHAB program as a collaboration with multiple partners and is now distributed to managers. The forecast is grounded in a mechanistic understanding of *Pseudo-nitzschia* bloom dynamics in the Pacific Northwest that has accumulated over two decades of research (Brown et al., 2012). ORHAB data and oceanographic data from NANOOS and other partners describing the environmental conditions that are known to support toxic bloom development in the eddy and bring toxic cells onshore to coastal beaches are synthesized by local experts to forecast HAB risk. The level of risk is communicated using a "traffic light" approach, where a green symbol indicates low risk and a red symbol indicates high risk. Placing the ESP in the pathway of toxic HAB transport to coastal beaches complements beach monitoring conducted as part of ORHAB and vastly improves the ability to forecast HABs via the Pacific Northwest HAB Bulletin.

Harmful algal blooms forecasting efforts in the Pacific Northwest are a premier example of how collaborative research and monitoring forms the foundation for valuable risk assessments of coastal hazards. Sustaining a system that allows for the integration of advanced technology and near real-time forecasts will allow for local tribes and state agencies to be proactive in their monitoring and management of coastal resources.

California

The leading HAB issue in California is *Pseudo-nitzschia* and the threat of ASP from DA via recreationally and commercially harvested molluscan and crustacean shellfish. These blooms occur annually and cause devastating impacts to local economies through fishery closures (McCabe et al., 2016) and, unlike in the Pacific Northwest, commonly lead to unusual mortality events (UMEs) in seabirds and marine mammals (e.g., Lefebvre et al., 1999; Scholin et al., 2000). Historically, ASP has been managed by state agencies: California Department of Public Health (CDPH), California Department of Fish and Wildlife (CDFW), and the Office of Environmental Health Hazard Assessment (OEHHA). Rigorous and routine academic involvement in monitoring for HABs began in 2008 with the advent of the California Harmful Algal Bloom Monitoring and Alert Program (Cal-HABMAP) that conducts weekly nearshore surveys at major piers and harbors of eight critical HAB taxa (e.g., *Alexandrium* spp, *Akashiwo sanguinea*) via light microscopy and the DA toxin via ELISA and LC-MS (Kudela et al., 2015). The program builds on NOAA MERHAB support and is sustained with support from the Southern California Coastal Ocean Observing System (SCCOOS) and the Central and Northern California Ocean Observing System (CeNCOOS). Immediate, qualitative results are reported through an email listserv to managers and interested stakeholders with periodic guidance from a standing steering committee comprised of state, federal, and academic partners. The quantitative and curated data are shared in a SCCOOS public archive. These data are progressively being made Darwin-Core compliant before being stored within the NOAA Environmental Research Division's Data Access Program (ERDDAP) for eventual ingest by the global Ocean Biogeographic Information System (OBIS) and by the United States IOOS Environmental Sensor Map[7]. The latter is true for all United States IOOS Regional Association data sets.

In response to the need for a predictive HAB capability in California, the California Harmful Algae Risk Mapping (C-HARM) System was developed to inform when and where toxic blooms occur to better inform management decisions. The NASA, NOAA National Centers for Coastal Ocean Science (NCCOS), and CA Ocean Protection Council-funded C-HARM project successfully generated and validated routine nowcast and forecast products in a research-to-operations demonstration of predictions of toxigenic *Pseudo-nitzschia* blooms and DA along the central California coast. Statistical ecological models are built from mechanistic understanding of blooms and driven in near real-time by information from hydrodynamic model simulations (Regional Ocean Model System) with three-dimensional variational data assimilation, satellite imagery, and community (Cal-HABMAP)/marine mammal observations (**Figure 2**; Anderson et al., 2016). Data that are routinely assimilated into the hydrodynamic model that are SCCOOS

[5]http://www.nanoos.org/products/real-time_habs/home.php

[6]http://www.nanoos.org/products/habs/forecasts/bulletins.php

[7]https://sensors.ioos.us/

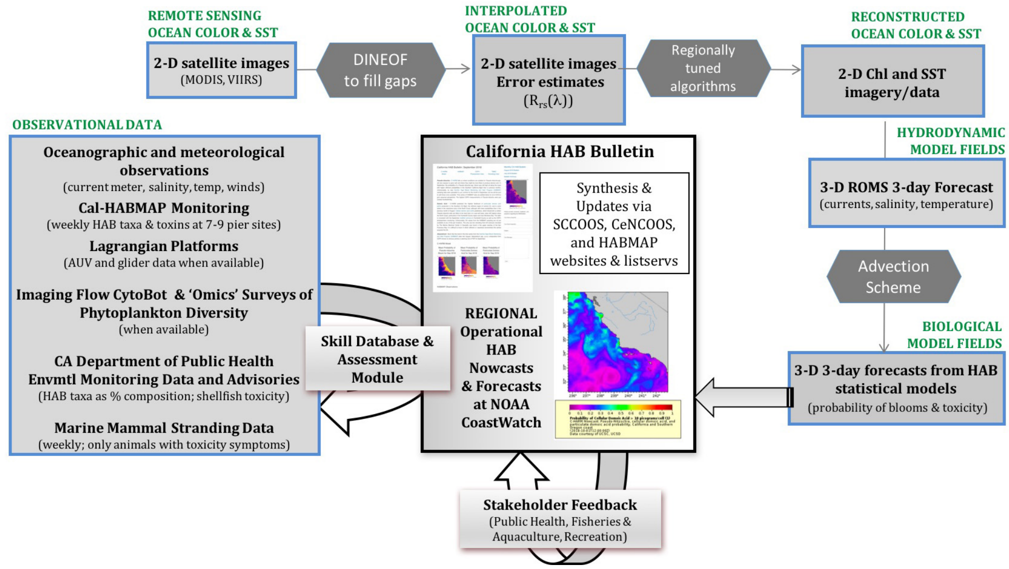


FIGURE 2 | An integrative schematic of the *in situ* data sets, remote sensing imagery, and model output that support production of the C-HARM system for blooms and domoic acid events. Stakeholder engagement is conducted via the monthly CA HAB Bulletin. Modified from Anderson et al. (2016).

and CeNCOOS-supported are: 1) operational, autonomous, underwater glider data (most are Spray gliders[8] and 2) daily high-frequency radar (HFR) measurements of surface currents (62 radar in CA[9]). Optical parameters required by the ecological models are retrieved from daily 1-km MODIS-Aqua satellite data and enhanced using Data Interpolating Empirical Orthogonal Functions (DINEOF) (Beckers and Rixen, 2003; **Figure 2**).

With the recent transition to operations of C-HARM at NOAA CoastWatch, this joint academic-government contribution will hopefully aid natural resource managers with early warnings of unusual mortality events of marine mammals, DA risk in wild fish stocks, and the need for more targeted sampling at commercial aquaculture sites. Pixel-level time series of model output are accessible via the CeNCOOS data portal, and all nowcast and forecasts can be easily visualized on the ERDDAP. Model validation is performed relative to the nearshore Cal-HABMAP sampling but would be greatly enhanced if offshore data were available to compare with the 3-km horizontal grid scale. Commercial fishing associations, marine mammal rescue groups, and public health managers provide frequent feedback on the utility of HABMAP and C-HARM and are engaged in the production of a California HAB Bulletin that synthesizes C-HARM predictions, HABMAP observations, marine mammal stranding records for DA toxicosis, and CDPH phytoplankton monitoring results as a monthly retrospective to stakeholders and to the public (**Figure 3**). The Bulletin is distributed via an electronic mailing list and publicly displayed on the SCCOOS[10] and HABMAP[11] websites.

[8]https://spraydata.ucsd.edu/
[9]http://www.sccoos.org/data/hfrnet/
[10]http://sccoos.org/california-hab-bulletin/
[11]http://www.habmap.info/

Integration of the Imaging Flow CytoBot (IFCB; Sosik and Olson, 2007; essentially an underwater microscope capable of collection and automated classification of water samples every ∼20 min) into the California observational repertoire has allowed monitoring of high-frequency variability in phytoplankton biodiversity at pier sites and as part of the shipboard time series (Kudela et al., unpublished data; Cloern, 2018), and may lead to the ability to detect HABs at their inception. Genetic surveys of *Pseudo-nitzschia* populations in Monterey Bay are conducted in tandem with deployments of the ESP in Monterey Bay on both moored and autonomous glider platforms (Scholin et al., 2009; Ryan et al., 2011), providing essential molecular information for understanding the subtle evolutionary variations driving toxic DA events (Bowers et al., 2016). We imagine that a new generation of small, easily deployed and even free-drifting swarms of autonomous sensors (Jaffe et al., 2017) for moieties like dissolved toxins and/or a network of moored and autonomous instruments like the IFCB and ESP will enable true early warning of blooms in the California Current System. As mentioned, a major observing gap is in the offshore environment where HAB data are critical for properly validating the moderate resolution C-HARM model output and for tracking offshore initiation of blooms. Another knowledge gap is a quantitative understanding of the transfer of DA from phytoplankton to higher trophic levels such that accurate predictions of food web impacts can be delivered to stakeholders.

Ultimately, the key to continued success of the California response to HABs is (1) strong communication between the many partners, (2) a better understanding of offshore bloom initiation, coastal-to-nearshore connectivity, and food web transfer of toxins to produce more accurate forecasts, and (3) continued investment by the state to ensure that rapid alerts are issued to the fishing and aquaculture communities as well as the public.

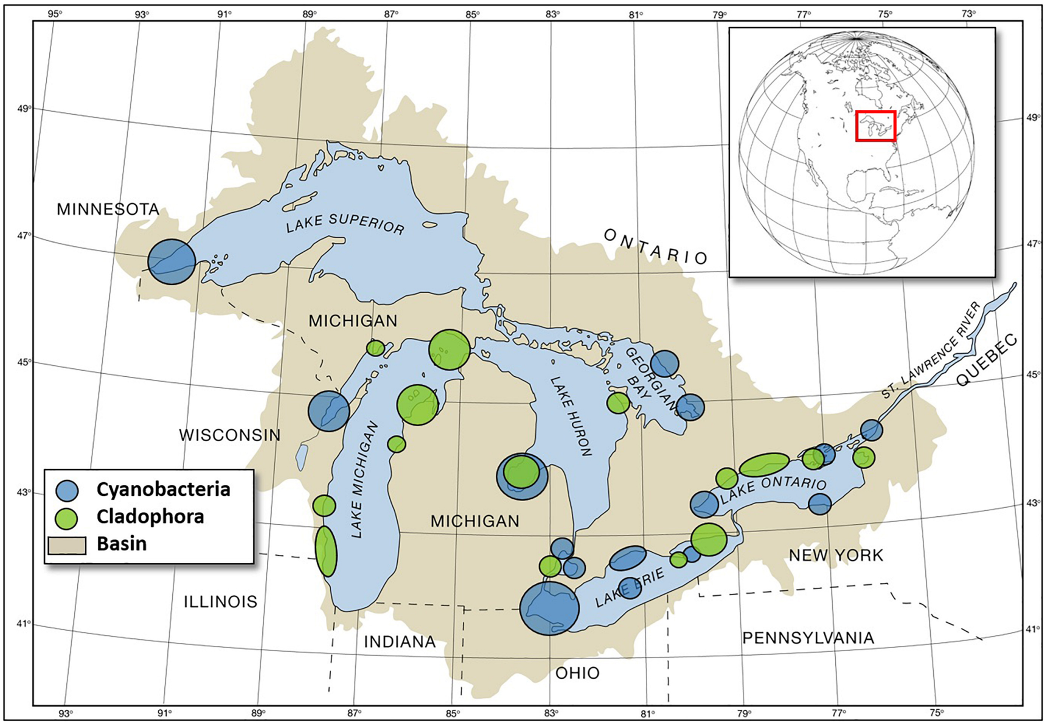


FIGURE 3 | Map of reported cyanobacterial and *Cladophora* HAB locations in the Great Lakes basin. (Graphic from National Science, and Technology Council [US] (2017); courtesy of GLERL/OAR/NOAA).

The Gulf of Mexico

The five US states bordering the northern Gulf of Mexico, Texas, Louisiana, Mississippi, Alabama, and Florida have all experienced HABs in their coastal waters. *Karenia brevis* is the most prevalent species in the Gulf of Mexico and is responsible for annual blooms that not only contaminate shellfish but also cause massive fish, marine mammal, and sea turtle mortalities. *K. brevis* produces a suite of neurotoxins, brevetoxins, that are not only released into the water but, when subjected to wind and wave action, are converted to marine aerosols (Pierce et al., 2005; Cheng et al., 2005). When inhaled, these airborne toxins cause respiratory distress in people, especially those who have asthma and/or other underlying lung diseases (Fleming et al., 2007; Kirkpatrick et al., 2011). Observations of *K. brevis* blooms are acquired primarily through traditional means, such as grab samples and microscopic enumeration. In recent years, new technology, such as the IFCB, has provided *in situ* monitoring off Texas (Campbell et al., 2013), and the Optical Phytoplankton Discriminator ("a.k.a. BreveBuster") has been deployed on both fixed platforms and autonomous underwater gliders in southwest Florida (Shapiro et al., 2015).

Current regulations mandate commercial shellfish harvest closures if *K. brevis* reaches 5000 cells per L, and it is the only HAB which has regulatory action tied to cell counts rather than toxin measurements. Heil and Steidinger (2009) published a summary of the monitoring for *K. brevis* in the Eastern Gulf of Mexico. The Florida Department of Agriculture is now the agency responsible for regulating shellfish harvest areas, while the Florida Fish and Wildlife Conservation Commission (FWC) is responsible for monitoring marine HABs in the state. They collate and analyze samples from numerous field partners, including citizen volunteers, and produce a weekly to bi-weekly status reports and hosts and interactive mapping tool[12]. The University of South Florida issues remote sensing products and forecasts of ocean currents to help stakeholders track *K. brevis* and associated impacts. Since 2004, NOAA has been producing the first operational HAB Bulletin weekly for the Gulf of Mexico[13] (Stumpf et al., 2009). Texas Parks and Wildlife posts status reports only when levels above background (1,000 cells/L) have been detected[14]. In Alabama, the monitoring is conducted by the Alabama Department of Public Health[15]. In Mississippi, the Department of Marine Resources monitors for *K. brevis* but does not post routine reports[16]. The Louisiana Department of Health's Molluscan Shellfish Program samples for *K. brevis* based on reports from surrounding states (TX and MS)[17]. Coordination across state lines occurs when a bloom covers multiple state waters or there is an unusual event warranting assistance for accurate species identification and biotoxin measurements.

[12]http://myfwc.com/research/redtide/statewide/

[13]https://tidesandcurrents.noaa.gov/hab/gomx.html

[14]https://tpwd.texas.gov/landwater/water/environconcerns/hab/redtide/status.phtml

[15]https://www.alabamapublichealth.gov/news/2018/11/21b.html

[16]https://www.facebook.com/MississippiDMR/posts/red-tide-update-for-the-gulf-coast/874997942608667/

[17]http://ldh.la.gov/index.cfm/page/629/n/210

Coordination between the United States and Mexico for *K. brevis* has been via the United States Environmental Protection Agency Gulf of Mexico Program (Soto et al., 2012). The collaboration provided capacity building, technology transfer, and joint research efforts between the two countries.

Citizen science programs are emerging as an effective approach for improving spatial and temporal coverage of HAB observations that directly support models and forecasts. In Texas, a group of Master Naturalists known as the Red Tide Rangers assist the state with sampling during a bloom event. On the west coast of Florida, lifeguard and park rangers file reports from a smartphone daily to provide qualitative information that a beach goer might be interested in – from the presence or absence of dead fish on the beach, to rip currents and wind speed and direction (Kirkpatrick et al., 2008). This program was implemented in 2006 and currently has 33 reporting sites. Two other ongoing projects also employ citizen science. The Nucleic Acid Sequence Based Amplification (NASBA) project trains volunteers to process water samples through a hand-held, battery-operated sensor that uses isothermal amplification coupled with fluorometry to detect and quantify *K. brevis* RNA using species-specific molecular beacons (Casper et al., 2007). The data are uploaded to a portal at the Gulf of Mexico Coastal Ocean Observing System (GCOOS) that estimates a cell count based on the RNA amplification profile relative to standards instead of the amount of RNA detected. A second project trains volunteers to process water samples using a microscope connected to a smartphone. Instead of counting cells, the volunteer takes a video of the sample. The video is then uploaded to a separate GCOOS portal, and deep learning software uses machine learning to automatically estimate a cell count from the video. The goal of this innovative sampling strategy is to reduce technical expertise/knowledge required by traditional microscopy and provide cell counts at a higher spatial and temporal scale than previously possible (Hardison et al., in prep). Daily input of data supports high-frequency forecasts of aerosolized toxins at beaches in three-hour time intervals. Beach goers can then decide where and when to visit beaches in order to minimize exposure to the toxic aerosols[18].

Due to the skill required for microscopic cell enumeration and the level of training required for accurate quantitation, stakeholders in the Gulf of Mexico are exploring new approaches for HAB observations. Some of these involve automation such as the ICFB and OPD, and some require employing citizen scientists to improve the spatial and temporal resolution of observation. Continuing to improve collaboration across state lines and international borders is also needed.

Gulf of Maine

The economic impact of HABs in the Gulf of Maine can be severe; a single fishery closure from a HAB threat in Massachusetts resulted in a loss of $18 million in 2005 (Jin et al., 2008). *Alexandrium fundyense* and associated PSP has historically been the focal HAB threat to human health in the Gulf of Maine, which is bordered by the United States states of Maine, New Hampshire, and Massachusetts, as well as by the Canadian Provinces of New Brunswick and Nova Scotia. Research monitoring efforts use ship-board surveys of cells in the water column as well as mapping of benthic cysts (Anderson et al., 2005, 2014) and more recently automated measurements with the ESP and IFCB (Brosnahan et al., 2015) to track bloom risk and severity. Coupled physical-biological models that combine the HAB population dynamics and hydrodynamics have facilitated hindcast and process-oriented studies (McGillicuddyJr., Anderson et al., 2005; He et al., 2008; Li et al., 2009). An annual cyst map is an important initial condition for the coupled biological-physical models that are also used for seasonal to sub-seasonal forecasts and to examine the effects of water mass anomalies when combined with observations (McGillicuddyJr., Townsend et al., 2011). The forecast configuration that uses ROMS is currently being transitioned into operations within the NOAA Center for Operational Oceanographic Products and Services (CO-OPS). More recently, blooms of *Pseudo-nitzschia* have led to unprecedented shellfish closures in Maine and Rhode Island, but not in Massachusetts, due to detection of ASP toxins.

Despite significant progress in understanding and managing HABs in the Gulf of Maine, many challenges remain. The three US states that border the Gulf of Maine all have monitoring activities focused on phytoplankton monitoring and toxin levels in shellfish. Information from these state monitoring activities, research activities, and the NOAA forecasts are shared via a controlled electronic mailing list. In addition to the state shellfish and phytoplankton monitoring, much of the work being funded is connected to research grants or rapid response projects. While there are routine oceanographic observations capable of discerning water masses in the region as part of the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS), there are no routine HAB observations to validate the model currently being transitioned to operational status at NOAA.

During a recent stakeholder workshop, the need for these observations and higher spatial resolution modeling along the coast was highlighted. The concept of a regional IFCB network for HAB early warning and better integration of all HAB data at a regional scale were also thought to have great potential.

United States Laurentian Great Lakes

Great Lakes HABs in freshwater, represented mostly by an array of cyanobacteria and submerged aquatic vegetation that disrupt ecosystems, damage local economies, and impact drinking water supplies. The Great Lakes case study is focused on the development of a Cyano-HAB observational capacity and forecasts by the NOAA National Ocean Service and OAR. However, comparable observational and forecasting development efforts are currently underway by the EPA, NOAA, United States Geological Survey (United States GS), and university partners to address the impact of the submerged aquatic vegetation *Cladophora* (**Figure 3**).

Great Lakes Cyano-HABs include *Microcystis*, *Dolichospermum, Aphanizomenon, Planktothrix,* and *Lyngbya* (**Figure 3**; National Science, and Technology Council [US], 2017). Observing and forecast systems have been developed

[18]https://habscope.gcoos.org/forecasts

for Lake Erie and are in development for other areas including Saginaw Bay on Lake Huron and Green Bay on Lake Michigan. The Lake Erie forecasts and observing systems were developed in response to a highly toxic bloom event in 2014 that resulted in the shutdown of the Toledo, OH drinking water intake (Steffen et al., 2017).

Forecast systems on Lake Erie addressing toxic *Microcystis* blooms include an operational forecast bulletin and a seasonal HAB ensemble forecast (Wynne and Stumpf, 2015). The seasonal ensemble forecast combines forecast products from NOAA, industry, and university partners and relies on satellite remote sensing time series and phosphorus loading data from the Maumee River (Stow et al., 2015; Wynne and Stumpf, 2015). Daily to weekly forecast bulletins, weekly sampling, the HAB Tracker[19], real-time buoys (Ruberg et al., 2007), and hyperspectral flyovers[20] provide a combination of environmental information decision support tools for regional managers. Forecast bulletins[21] produced by the NOAA CO-OPS, NCCOS, and the Great Lakes Environmental Research Laboratory (GLERL) employ satellite remote sensing and coastal circulation to generate a five-day HAB outlook combined with bloom toxicity results obtained from weekly sampling and the deployment of near real-time ESPs (Scholin et al., 2009; Ryan et al., 2011). Real-time buoys provide hourly observations[22] of parameters such as winds, waves, phycocyanin (a characteristic pigment of cyanobacteria), chlorophyll, and nutrients to provide awareness of HAB development and to distinguish wind-driven resuspension of nutrient inputs from river contributions. Weekly flyovers of drinking water intakes using a hyperspectral imaging sensor (Vander Woude et al., 2019) provide observations in the nearshore and below the cloud layer that usually interferes with satellite remote sensing retrievals. Many of these observations are accessed through the Great Lakes Observing System (GLOS) HAB Data Portal[23].

Great Lakes HABs observations are becoming increasingly automated as two additional Monterey Bay Aquarium Research Institute (MBARI) Second Generation ESPs will be deployed in Lake Erie with the real-time capacity to detect microcystin. With the successful demonstration of the MBARI Third Generation (3G) ESP autonomous underwater vehicle (AUV) during the 2018 HAB season with NCCOS, OAR, and the Cooperative Institute for Great Lakes Research (CIGLR) partners, further demonstrations of the 3G AUV system are planned for 2019 testing of real-time saxitoxin and microcystin sensors.

This combination of forecast and observational tools currently provides the awareness that was lacking when HAB toxins impacted the Toledo water intake in 2014. Information is now available to drinking water managers and the public providing advanced warning of changing lake conditions. This information is valuable for planning drinking water treatment as well as coastal recreational activities. Future research is now focused on the reliable detection and forecasting of HAB toxicity.

The United States Caribbean Islands

The Caribbean region is mainly affected by two significant HABs: "golden tides" caused by the accumulation of the macrophyte *Sargassum* in coastal zones and ciguatera fish poisoning, endemic to tropical areas, due to the consumption of fish contaminated by ciguatoxins synthesized by unicellular benthic microalgae (see below). These are very different types of HABs that require specialized observing approaches.

Pelagic *Sargassum* constitutes a unique habitat for fishes and invertebrates. For this reason, the Sargasso Sea, an area where these macroalgae naturally proliferate was identified as an Ecologically or Biologically Significant Area (EBSA) by the Convention on Biological Diversity[24]. *Sargassum* is transported by ocean currents to coastal zones, and in the last 15 years, in particular in 2014–2015 (Schell et al., 2015; Hu et al., 2016), massive accumulations (100 kg wet wt/m^2) have been documented in bays and beaches of the Gulf of Mexico, Caribbean Islands (as well as in West African Atlantic coasts). *Sargassum* beachings cause economic losses to coastal fisheries and tourism, alter the dynamics of the shoreline ecosystems, and the hydrogen sulfide produced by the seaweed decomposition can also affect human health (Dabor et al., 2018; Langin, 2018). These negative impacts have fostered research to understand the factors involved in *Sargassum* bloom dynamics. An improved understanding of the spatial distribution (from open sea to coastal zones) in biomass, including seasonality, inter-annual variability, and long-term trends is achieved thanks to recent advances in remote sensing of *Sargassum* using Landsat, MODIS, and MERIS. Two systems, SEAS (Webster and Linton, 2013) and Satellite-based *Sargassum* Watch System (SaWS) (Wang and Hu, 2016, 2017), are now operational. The Sargassum Outlook monthly bulletin[25] offers a quick assessment of the magnitude of the *Sargassum* blooms since 2011 and strongly suggest that *Sargassum* concentrations during 2018 have exceeded the 2015 event (**Figure 4**). Observations have revealed the existence of a recurrent "*Sargassum* belt" extending from western Africa to the Caribbean Sea and Gulf of Mexico (Franks et al., 2016; Putnam et al., 2018) that has potentially created a "new Sargasso Sea" (Gower et al., 2013). CARICOOS, the Caribbean Coastal Ocean Observing System, publishes daily imagery of Floating Algae Index in the region (Franks et al., 2016)[26] issued by the Optical Oceanography Laboratory at the University of South Florida. An ongoing effort led by H. Hoarty at Rutgers University and supported by CARICOOS (Prakash et al., 2018) utilizes surface current data derived from high-frequency radar (HFR) coupled to satellite imagery to forecast *Sargassum* arrivals into the CARICOOS region.

Ciguatera fish poisoning (CFP) is caused by the ingestion of fish (e.g., Friedman et al., 2017 and references therein) or shellfish (Darius et al., 2017) contaminated with neurotoxins (ciguatoxins

[19]https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habTracker.html

[20]https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/airSatelliteMon.html

[21]https://tidesandcurrents.noaa.gov/hab/lakeerie_bulletins/bulletin_current.pdf

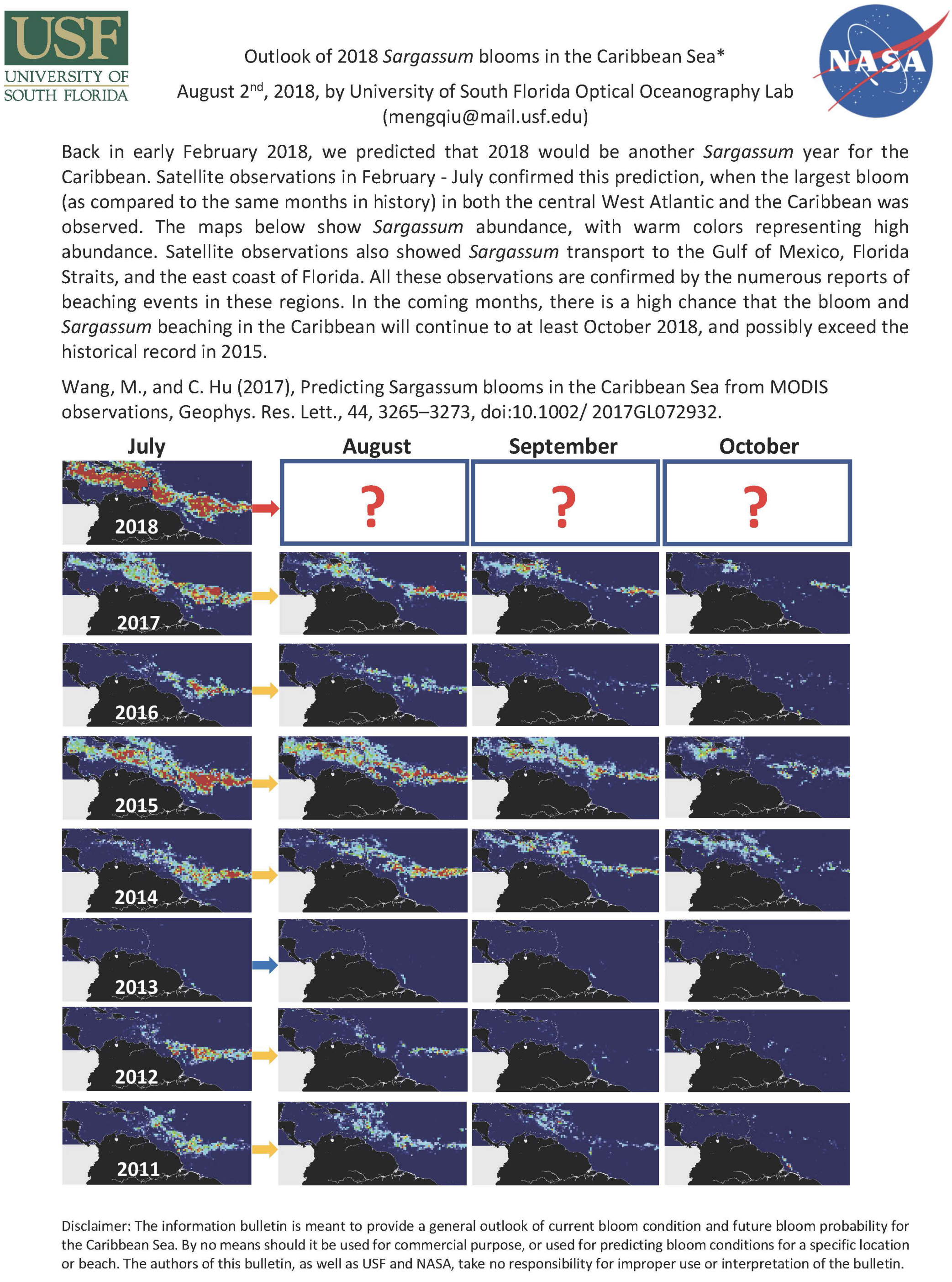
[22]https://www.glerl.noaa.gov/metdata/

[23]http://habs.glos.us/map/

[24]https://www.cbd.int

[25]https://optics.marine.usf.edu/projects/SaWS.html

[26]https://www.caricoos.org/oceans/observation/modis_aqua/ECARIBE/afai


Outlook of 2018 *Sargassum* blooms in the Caribbean Sea*

August 2nd, 2018, by University of South Florida Optical Oceanography Lab (mengqiu@mail.usf.edu)

Back in early February 2018, we predicted that 2018 would be another *Sargassum* year for the Caribbean. Satellite observations in February - July confirmed this prediction, when the largest bloom (as compared to the same months in history) in both the central West Atlantic and the Caribbean was observed. The maps below show *Sargassum* abundance, with warm colors representing high abundance. Satellite observations also showed *Sargassum* transport to the Gulf of Mexico, Florida Straits, and the east coast of Florida. All these observations are confirmed by the numerous reports of beaching events in these regions. In the coming months, there is a high chance that the bloom and *Sargassum* beaching in the Caribbean will continue to at least October 2018, and possibly exceed the historical record in 2015.

Wang, M., and C. Hu (2017), Predicting Sargassum blooms in the Caribbean Sea from MODIS observations, Geophys. Res. Lett., 44, 3265–3273, doi:10.1002/ 2017GL072932.

Disclaimer: The information bulletin is meant to provide a general outlook of current bloom condition and future bloom probability for the Caribbean Sea. By no means should it be used for commercial purpose, or used for predicting bloom conditions for a specific location or beach. The authors of this bulletin, as well as USF and NASA, take no responsibility for improper use or interpretation of the bulletin.

FIGURE 4 | University of South Florida *Sargassum* Outlook monthly bulletin for *Sargassum* abundance in the Caribbean from SaWS (Satellite-based *Sargassum* Watch System).

and/or maitotoxins) produced by the benthic dinoflagellates in the genera *Gambierdiscus* and *Fukuyoa*. CFP is the most frequently reported, non-bacterial illness endemic in tropical regions and produces a complex array of acute gastrointestinal, neurological/neuropsychological, and cardiovascular symptoms that can become chronic after repeated exposure to these toxins. Recent improvements in sampling, taxonomic characterization, and sophisticated toxin detection indicate that CFP-producing species may be spreading from tropical to temperate latitudes due to global warming (Tester et al., 2010; Laza-Martínez et al., 2016; Rodríguez et al., 2017; Nishimura et al., 2018). Phenological changes may also be occurring in CFP-prevalent areas such as the Caribbean Sea (Tosteson, 2004; Nakada et al., 2018). Protecting human health requires efficient monitoring of the benthic species and their toxins, seafood, and improved epidemiology surveillance.

New approaches, such as the artificial substrate sampling method (Tester et al., 2014), have been successful in detecting new benthic species worldwide. The challenge is to prevent CFP in local populations whose main protein source is seafood, and one possible solution would be the banning of commercial sales of species that have been consistently linked to poisoning events, such as barracuda (Reglamento de Pesca de Puerto Rico, 2004[27]). Recent studies suggest that the spatial distribution of toxic fish is defined by environmental gradients in grazing (Loeffler et al., 2018), wave energy (Loeffler et al., 2015), and temperature. These results suggest the possibility of establishing guidelines for "no take" zones as a risk management strategy. CARICOOS acquires environmental data, including wave observations and models, which has been key for identifying conditions linked to ciguatoxin concentration in commercially harvested fishes in the Virgin Islands (**Figure 5**).

Precise toxin detection and quantification is possible by LC-MS in accredited laboratories and by fluorescence-based receptor binding assay (RBA-F), Hardison et al., 2016), an alternative method used to screen fish samples for ciguatoxins in facilities that are not certified to use isotopes. However, the development of affordable, reliable, and fast detection methods available to the general population and medical community is fundamental. The protection of human health also requires efficient diagnosis and reporting. The annual prevalence of CFP worldwide has been estimated to be around 50,000–100,000 cases, but these values could represent only 20% of actual cases, due to misdiagnosis and under-reporting (Gatti et al., 2018). Thus, in addition to monitoring *Gambierdiscus* and its toxins, efficient public health surveillance is mandatory. A successful approach has been implemented in French Polynesia after 20 years of effort (Morin et al., 2016; Gatti et al., 2018), making this region a reference for other areas of the world. Since 2007, the multidisciplinary and coordinated research between the Institut Louis Malardé (ILM) and the Public Health Directorate of French Polynesia have facilitated assessing the current CFP status on different archipelagos, provided a quantitative estimate of the health-related costs imputed to this illness, established outreach activities to document the risk perception and describe associated avoidance strategies among tourists, and professional and non-professional fishermen and, identified novel vectors of ciguatera poisoning.

[27]http://app.estado.gobierno.pr/ReglamentosOnLine/Reglamentos/6768.pdf

In summary, intrinsically different organisms, macroalgal *Sargassum* and microscopic *Gambierdiscus,* threaten human health and fragile economies in these tropical areas. In this context *Sargassum* and *Gambierdiscus* are fundamental ecological variables that can structure coordinated regional and observing systems in the Caribbean and Gulf of Mexico. CARICOOS through satellite observing and dissemination tools is proving suitable as an early warning system for the detection of massive *Sargassum* beachings along Caribbean coasts. In coordination with other research technologies, CARICOOS can contribute to understanding *Sargassum* biology and bloom dynamics and will help to design mitigation strategies on the massive biomass accumulations in coastal areas. Finally, effective monitoring of benthic dinoflagellates and ciguatoxins is a main challenge for the tropical areas and require efforts on new technologies. Here, international cooperation in the development and implementation of cost-effective sampling and probes will be decisive for protection of human health in economically fragile areas.

Asia

Harmful algal blooms in Asia have long been recognized as a serious threat in coastal ecosystems, fisheries, and public health. The best documented impacts are associated with "red

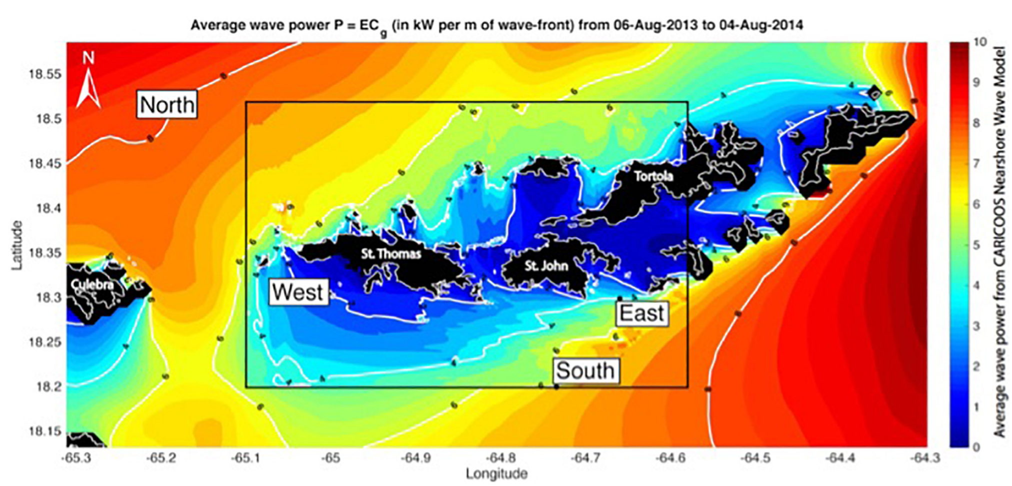


FIGURE 5 | Average wave power per unit wave crest in the United States Virgin Islands computed using model output from the CARICOOS Nearshore Wave Model. Site locations are within the white boxes (Loeffler et al., 2018).

tide" outbreaks of *Noctiluca, Trichodesmium, Heterocapsa,* and *Cochlodinium* (now *Margalefidinium*) (GEOHAB, 2010b; c.f. Red Tides in Korea special issue, *Harmful Algae* 30, 2013), although massive green tides, such as blooms of the macroalgae *Ulva* (= *Enteromorpha*) *prolifera* and *Cladophora* species as well as the green variant of the dinoflagellate *Noctiluca scintillans*, are also prevalent, particularly in the Yellow Sea (GEOHAB, 2010b; Liu and Zhou, 2018). Since the 2000s, other harmful organisms have caused massive fish kills and economic disruption in regions where large-scale HAB events associated with these organisms were rare or unreported (c.f. Furuya et al., 2018). For example, *Karenia mikimotoi* has been identified with increasing frequency in China, Japan, Korea, Hong Kong, and Singapore (Okaichi, 2004; Qi et al., 2004; Leong et al., 2015), while the dinoflagellates *Akashiwo sanguinea, Gonyaulax polygramma, Prorocentrum* spp., and *Scrippsiella trochoidea*, as well as the diatoms *Pseudo-nitzschia* spp. and *Chaetoceros* spp., have emerged as HABs (c.f. Furuya et al., 2018). Known HAB organisms have also expanded to new regions, with (for example) *Karlodinium australe* causing massive fish kills in Johor Strait Malaysia in 2014 (Lim et al., 2014) followed by even more damaging blooms in subsequent years (Teng et al., 2016).

Direct toxicity in shellfish, finfish, and humans is also well documented, with more than 2,000 PSP cases reported in Southeast Asia, approximately 10% of which caused fatalities (Furuya et al., 2018), while other lipophilic toxins (okadaic acid, azaspiracid, pectenotoxin, yessotoxins, gymnodimine, and spirolides) and DA are also present (c.f. Furuya et al., 2018). As with other regions globally, benthic HABs including *Coolia* spp. and *Gambierdiscus* spp. are also emerging as potential threats.

Given the long history of HABs in Asia, many local monitoring programs have been in effect for decades, gradually developing into national and regional efforts. For example, a massive *Margalefidinium polykrikoides* bloom in Korean coastal waters in 1995 led the National Fisheries Research and Development Institute (NFRDI) to develop a national (South Korea) monitoring program that coordinates more than 30 local offices (Lee et al., 2013). Similar efforts to standardize research, monitoring, and prediction at a national level were implemented under the auspices of the Chinese Ecology and Oceanography of Harmful Algal Blooms (CEOHAB) and Ecology and Oceanography of Harmful Algal Blooms in the Philippines (PhilHABS) programs.

Beyond these local and national efforts, in response to the recognition of regional HAB threats, a regional plan has emerged for HAB research focused on cooperation in Asia. This developed out of two meetings (Tokyo, Japan, 2007. and Nha Tang, Vietnam, 2008) held in coordination with IOC/WESTPAC and the IOC HabViet Program, culminating in the GEOHAB Asia Regional Comparative Program (GEOHAB, 2010b). The meeting report gave an overview of Asian HAB problems and provided a framework for guiding priorities for research. The need to develop a comparative, international program on HABs in Asia was particularly compelling because Asia (1) is characterized by the highest production of aquaculture fish and shellfish globally, and thus the greatest impacts from HABs on these resources; (2) has a diversity of harmful syndromes (documented briefly above); (3) is experiencing an apparent trend of increasing HABs throughout the region and an increasing trend toward regional eutrophication linked to HABs.

Today there are multiple regional coordinating groups in Asia, including IOC/WESTPAC-HAB (formed in 1989), The Northwest Pacific Action Plan (NOWPAP), a part of the Regional Seas Programme of the United Nations Environment Programme (UNEP), adopted in 1994, the North Pacific Marine Science Organization (PICES) section on HABs, formed in 2003, and the Targeted HAB Species in the East Asia Waters (EASTHAB) established in 2004 (GEOHAB, 2010b). All of these coordinating bodies support standardization of best practices across the region, training and capacity building, and dissemination of scientific knowledge. A key lesson learned from this successful approach is that successful programs recognize and develop interfaces among all actors in the region for their mutual benefit, with flexibility regarding implementation at the local, national, and regional levels.

As with other regions, multiple approaches have been taken to address the HAB problem in Asia. In addition to coordination and capacity building, many countries and regions have implemented integrated monitoring and modeling systems for both freshwater and marine HABs (e.g., PICES, 2014; Jeong et al., 2015; Srivastava et al., 2015; Furuya et al., 2018; Yñiguez et al., 2018; Yu et al., 2018), often relying heavily on satellite remote sensing (e.g., Ahn and Shanmugam, 2006; Ye et al., 2011; Lee et al., 2013) for high biomass blooms. Many of these programs continue to innovate as new technologies become available. In Korea, for example, monitoring programs are evaluating the use of acoustics (Kang et al., 2016), molecular methods such as digital PCR (Lee et al., 2017), unmanned aerial vehicles (Oh et al., 2016), and new satellite platforms such as the Geostationary Ocean Color Imager (GOCI) coupled to numerical models to provide real-time decision-support tools for managers (Kim et al., 2017).

Asia is also a region where more proactive, mitigative measures have been refined, particularly the use of coagulants for high-biomass blooms, but also various biological and chemical methods (c.f. Yu et al., 2018). For clay flocculation, the basic principle is that charge differences between the flocculating agent and cell membranes causes adsorption via ionic bonding, and the algal cells sink from the water column. Natural (Park et al., 2013) and modified clays (Yu et al., 2017) are the prime mitigation techniques in South Korea and China, respectively, and have been used elsewhere, including freshwater systems (Li and Pan, 2013). Other mitigation used in Asia and elsewhere includes addition of chemicals, ozonation, electrolysis, and acoustic disruption [reviewed by Anderson et al. (2017)]. Biological control has also been proposed in Asia. Jeong et al. (2003) have proposed using heterotrophic dinoflagellates to control HAB events, while Imai et al. (2006) and Onishi et al. (2014) have identified plant- or macroalgae-associated naturally occurring bacteria that have lytic effects on a variety of HAB organisms, including *Heterosigma akashiwo, Karenia mikimotoi, Alexandrium tamarense*, while Shi et al. (2018) isolated a highly algicidal bacterial strain naturally occurring in a bloom of *Prorocentrum donghaiense*, leading to the proposed use of algicidal bacteria as a direct mitigation strategy (Meyer et al., 2017).

While these methods, particularly clay flocculation, have proven effective for targeted mitigation, there is also a strong need for continued research on the economic and ecological impacts of HABs, on observation and prediction, as well as on control of land-based pollution and coastal eutrophication to reduce the rapid proliferation of HABs in the region (Glibert, 2014; Yu et al., 2018).

The European Union (EU)

Throughout the 1990s, an early HAB warning system was identified as a key industry need to help farms plan seafood harvesting schedules in order to avoid severe financial losses after a series of prolonged closures in shellfish production areas. A reliable HAB warning system would give producers a chance to change their husbandry practices, e.g., avoid handling shellfish, proactively relocate stocks, harvest shellfish earlier or cancel a delivery in order to minimize losses and waste due to contaminated stock, or, increase harvesting prior to a HAB event. Scientists, industry, and regulators began to discuss how this accumulated knowledge could help assess the likely risk of HABs.

In the early 2000s, a number of research projects were initiated (e.g., the internationally funded HABWATCH, the European fifth and seventh Framework/Commission-funded HABES, HABBUOY, HABIT, MIDTAL, NEMEDA, and Irish BOHAB project) to investigate HAB transport, growth and physiology, biophysical interactions, and algal mortality in EU shellfish areas. The projects focused on enhancing the understanding of the environmental factors and oceanographic phenomena that influence HAB-shellfish toxic pathways, including the role of thin layers, horizontal advection, physical forcing mechanisms such as eddies, gyres, frontal systems, bottom density fronts, upwelling and downwelling events, seasonally formed bottom density fronts and associated jets, alongshore winds and wind exchange events (e.g., Raine et al., 2010; Raine, 2014). These scientific studies were also instrumental in the development and testing new technologies and methodologies (e.g., Lunven et al., 2005, 2012). New conceptual models were formulated using the observed, regional, physical forcing mechanisms and local circulation patterns, and knowledge of biophysical mechanisms that influence the distribution and cross shelf transport of HABs into aquaculture bays (Aleynik et al., 2016; Pinto et al., 2016). By 2008, it was clear that an integrated approach was needed to provide near real-time and forecast information services for the aquaculture industry. Armed with an improved understanding of HAB ecology, European scientists were in a position to exploit research outputs of past projects and work toward building a near real-time predictive HAB capacity, supported by the now well-established national phytoplankton and biotoxin databases.

In 2013, an EU-funded project, ASIMUTH (Applied Simulations and Integrated Modeling for the Understanding of Toxic and HABS), led by Ireland with partners from Portugal, Spain, France and Scotland, focused on HABs in NE Atlantic European shelf and coastal waters. The project endeavored to develop forecasting capabilities to warn of impending HABs (Davidson et al., 2016). Steps to achieve this included a series of scientific and technical objectives to enable the use of numerical modeling of physical – biological interactions to help forecast toxic shellfish events, fish mortalities, and ecological disruption from HABs. Ireland automated an operational service to provide a three-day prediction of water movements in the vicinity of Bantry Bay off the SW coast of Ireland, historical and current HAB and biotoxin data, and satellite-derived data products to produce a bulletin with expert interpretation of the likely HAB occurrence in the days ahead. A gap identified, as with many regions previously discussed, was that offshore observatories that provide near real-time information on HABs are missing. However, the ASIMUTH approach successfully demonstrated the power of integrating information and data products from multiple disciplines (remote sensing, physics, biogeochemistry, biology and ecosystems) to create a risk analysis/forecasting downstream service to assist farm management decisions to mitigate the potential negative HAB impacts (e.g., Cusack et al., 2016; Maguire et al., 2016; Ruiz-Villarreal et al., 2016). Data used to create the downstream service are available through the Copernicus Marine Environmental Monitoring Services (CMEMS), national biotoxin and phytoplankton monitoring programs, and from satellite providers (e.g., NASA and ESA data processed by IFREMER).

Active EU research projects such as CoCliME[28] (*Co-development of Climate services for adaptation to changing Marine Ecosystems* co-funded by ERA4CS JPI-climate), PRIMROSE (*Predicting Risk and Impact of Harmful Events on the Aquaculture Sector* funded by Interreg Atlantic Area) and Alertox-Net[29] (*Atlantic Area Network for introduction of Innovative Toxicity Alert Systems for safer seafood products* funded by Interreg Atlantic Area) foster interdisciplinary and transnational cooperation. Their efforts aim to improve the predictive capabilities of HAB events, enhance HAB management and monitoring practices, and support decision-makers through a co-development approach to clearly identifying stakeholder needs (**Figure 6**).

CoCliME focuses on the potential future climate-driven shifts of HABs, marine biotoxins, pathogens and marine microbial biodiversity that have direct impacts on human health (food-borne poisoning and water-quality related health disorders), economic prosperity (fisheries, aquaculture, tourism) and social well-being (recreation). Europe's coastal and shelf seas are the target regions for the CoCliME case studies; areas where the greatest impact is felt from harmful microorganisms on populations and commercial sectors of both water quality and seafood safety. The overall CoCliME aim is to co-develop and co-produce bespoke, proof-of-concept or prototype marine ecosystem climate services. The transdisciplinary team includes natural and social scientists, decision makers, and users of climate services that dynamically interact to identify common and priority climate change-related vulnerabilities and solutions. CoCliME plans to focus on local issues in six European focus areas (case studies include Atlantic Ireland, Atlantic French, Baltic, Black Sea, Mediterranean and North Sea/Norwegian Sea). Current activities include historic data analysis to identify any dependencies between HAB events and known environmental

[28]www.coclime.eu

[29]https://www.alertox-net.eu/

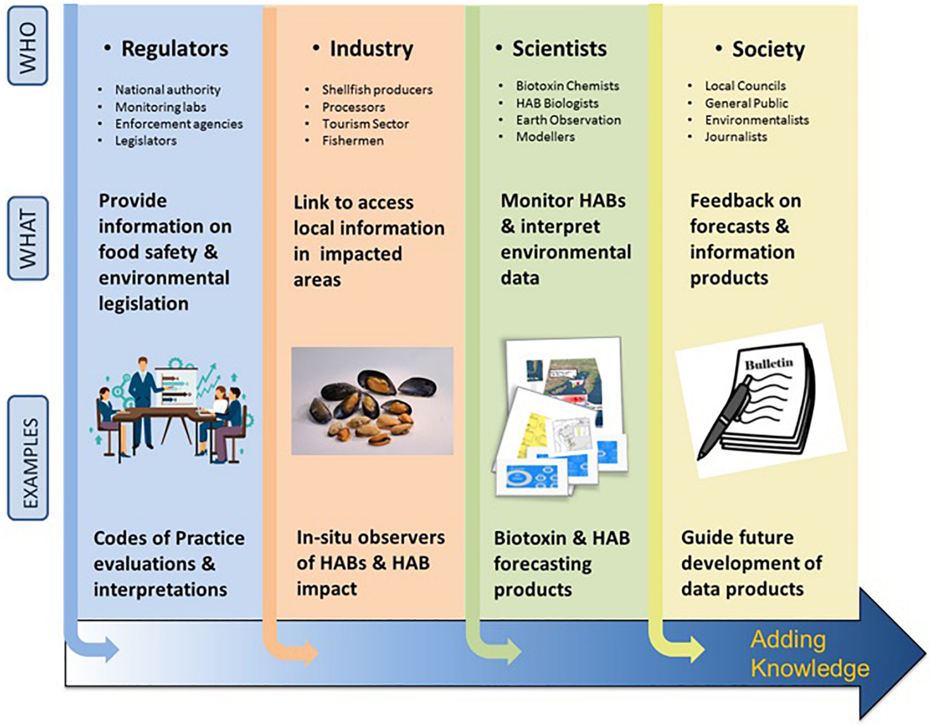


FIGURE 6 | HAB value chain: application of knowledge along the pathway to forecasting bulletin production from different sectors, regulators, industry, scientists and society and examples of the knowledge they provide. "Users" of the products along the chain are vital as they provide expertise to determine the HAB forecast and other data-derived products (https://www.coclime.eu/project-overview/co-development-processes).

factors related to climate change, which will help to estimate the likelihood of future HAB events when coupled with numerical model climate projection outputs. Climate service prototypes are being co-developed with stakeholders in industry, public health officials, and policy makers in each case study region to ensure maximum impact. This close engagement between the project teams allows the users to help guide the scientific work; for example, determining the time scales they are interested in for future climate projections. A transferable framework for climate services development is needed globally to support informed decisions relevant to climate change-related ecological and socio-economic impacts in coastal regions. The CoCliME results will feed into mechanisms such as the UN Sustainable Development Goals, EU Marine Strategy Framework Directive (MSFD), Marine Spatial Planning (MSP), national monitoring and reporting requirements, and climate adaptation planning to ensure the protection and sustainable use of Europe's marine and coastal ecosystems for future generations.

The aforementioned ASIMUTH project developed the methodology for producing HAB risk alerts to aquaculture and continues to publish them weekly with some partner countries. Continuing the development of this theme, the project PRIMROSE was initiated in late 2016 among ten Atlantic area partners from five EU member states. It aims to develop improvements to these alerts using operational oceanographic forecasts, downscaled regional hydrodynamic models, novel satellite data, HAB / toxin monitoring data, and expert evaluation (Leadbetter et al., 2018). PRIMROSE will upgrade this service to a regional scale and provide mesoscale trans-national HABs and microbial risk information and knowledge exchange with the user community. The project has commenced to develop close involvement/co-development with industry partners throughout the project to ensure maximum impact of the project outcomes. New information coming from the Marine Strategy Framework and Water Framework Directives monitoring programs and from a new generation of sensors aboard the Sentinel suite of satellites, deployed using drone technology and aboard buoys in marine locations will be utilized for the alert system. Other new features will include:

- The existing system will be expanded into new areas and new species (S and NW Spain, Canary Islands, Shetlands)
- Forecasting of shellfish bacterial contamination to account for microbial risk (e.g., *E. coli*, *Norovirus*, *Vibrio*) will be developed
- The potential for mitigation will be explored
- A Climate / Environmental change 10 year + product to evaluate future risk from harmful effects will be developed
- Policy makers, risk regulators, food safety authorities and the industry will be included

Alertox-Net, which also commenced in late 2016 among 14 EU partners, has a principal objective to facilitate market delivery of safer marine food products by putting urgently needed innovative toxicity alert systems in the value chain. In this project, the main toxins targeted are emerging toxins, non-regulated marine toxins that have proliferated in the Atlantic Area as a consequence of climate change and which are harmful toward public health. The system consists of cost-effective, easy-to-understand, detection and alert methods, which will facilitate adoption by industry. Furthermore, Alertox-net will recommend a regulatory framework addressed to authorities regarding emerging toxins, including tetrodotoxins, palytoxins, and cyclic imines. Moreover, the alert system will be developed for toxins that are currently regulated so that industries which are not adapted, e.g., they are not aware of the toxins and methods, can benefit from better protected products for their consumers (**Figure 7**).

In the Mediterranean, a recent threat deserves attention: the proliferation of the benthic dinoflagellate *Ostreopsis*. Since the late 1990s, the tropical genus *Ostreopsis* has been increasingly detected in many beaches of the Mediterranean Sea, reaching high cell abundances in some areas (**Figure 8**). *Ostreopsis* cf. *ovata* benthic HABs have been linked to massive mortalities of benthic fauna and mild respiratory irritations in people exposed to marine aerosols (Vila et al., 2016. and references there in). The genus also produces potent toxins (palytoxins and analogues) that were associated with dramatic seafood poisonings in tropical latitudes (Randall, 2005). Despite the toxins having been found in marine fauna in the Mediterranean, seafood-borne poisonings have not yet been reported in this area. So far, *Ostreopsis* blooms have only caused touristic impacts in the Mediterranean (Funari et al., 2015). However, the toxins have been rarely detected in the air (Ciminiello et al., 2014), while the presence of cell debris in the aerosol were confirmed by combining Scanning Electron Microscope and PCR (Casabianca et al., 2013). The recurrence of these events has stimulated coordinated research in the area, in particular through the RAMOGE Accord[30] and national and EU-funded projects. Multidisciplinary approaches involve scientists, public health and environmental authorities, and affected citizens. Common sampling, monitoring (Mangialajo et al., 2017), communication and outreach activities, including citizen science are also underway to design prevention strategies before *Ostreopsis* blooms constitute a major problem in this highly anthropized area.

[30]http://www.ramoge.org/fr/default.aspx

Years of coordinated projects and improvements to regulatory monitoring programs in Europe have proven effective for protecting human health from seafood poisoning. It is now time for progress in ecological modeling and climate projections to ascertain future trends of HABs in the European Seas due to the combined anthropogenic pressures and climate heating and to design mitigation strategies. Today, emerging blooms that cause mild respiratory irritation and biotoxins that cause potential seafood poisoning (associated with benthic *Ostreopsis* blooms) constitute a new challenge that requires an adaptive monitoring design to include the benthos. In all cases, communication with the general public, stakeholders, and policymakers is becoming urgent and is the best tool to address future strategies. Multiple ocean observatories should be identified within the very distinct marine ecosystems of the EU that can help support both hindcast and forecast models.

SYNTHESIS OF REGIONAL CASE STUDIES

Recent progress in several areas of technology, coupled with advances in our knowledge of biological behavior, such as HAB life history and oceanographic processes, has pointed toward a potential transformation in the way that we currently monitor, manage, and understand HABs. Rapid progress in bio-optics is providing hyperspectral signatures of water bodies associated with various HABs (Babin et al., 2005; Blondeau-Patissier et al., 2014; Muller-Karger et al., 2018a). Developments in imaging

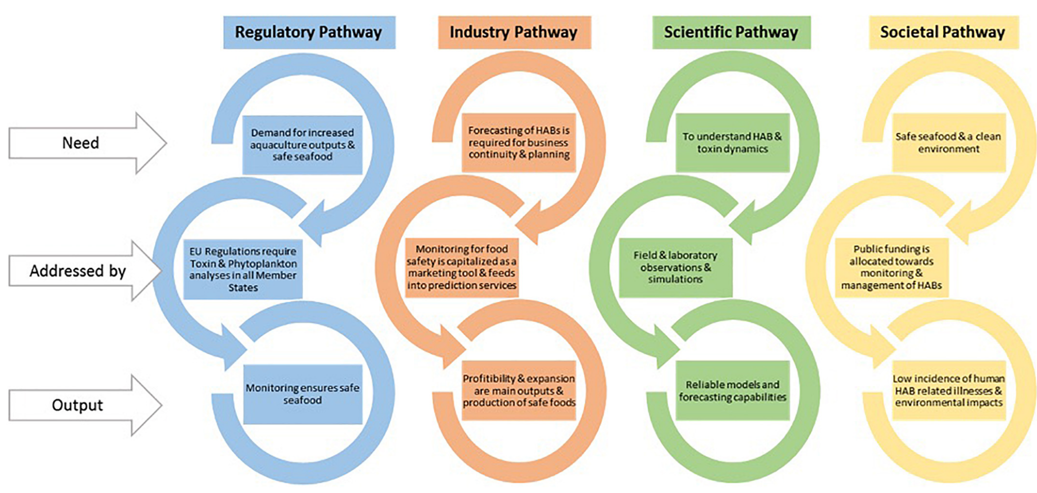


FIGURE 7 | Different sectors have different priorities for HAB and shellfish toxin forecasting in the EU (https://www.coclime.eu/project-overview/co-development-processes).

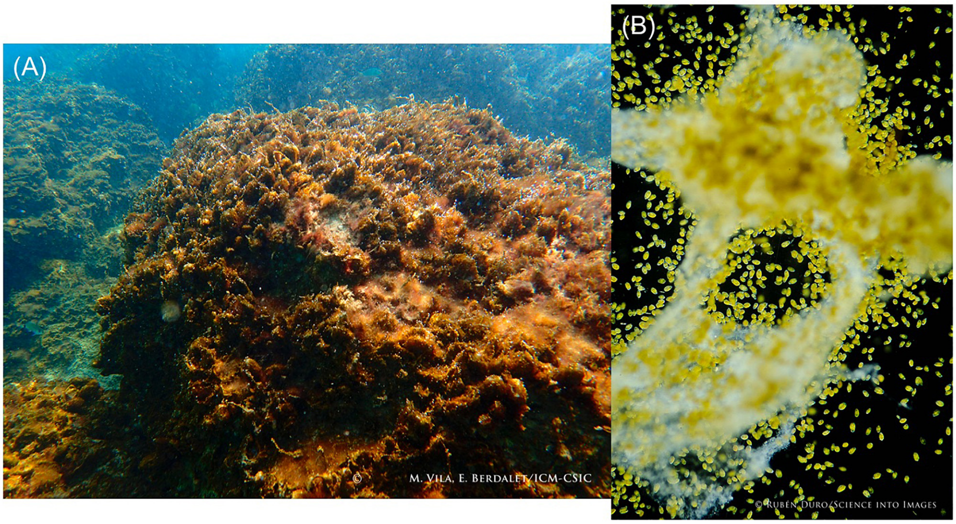


FIGURE 8 | Bloom of the benthic dinoflagellate *Ostreopsis* cf. *ovata* in the NW Mediterranean coast. **(A)** Mucilaginous biofilm covering the macroalgae (photo credit: M. Vila and E. Berdalet). **(B)** Microscopic image of *Ostreopsis* cells and the mucus produced to attach to the surfaces (magnification 4x) (photo credit: @RUBEN DURO/SCIENCE INTO IMAGES).

flow cytometry and particle size analysis have enabled better automation of bloom identification (e.g., Campbell et al., 2013). Progress in molecular biology has led to the development of next-generation molecular tools (Kudela et al., 2010). New technologies and modeling capabilities combined with more traditional biogeochemical methods will no doubt improve our understanding of HAB and seafood toxicity dynamics. Indeed, many of these technologies and methods for studying algae, primarily plankton, are described in detail by Boss et al., 2019 (in this Special Issue). The focus of the present contribution has been on regional programs where many of these newer technologies, such as the ESP and IFCB, are being evaluated for long-term, stakeholder-relevant HAB monitoring and mitigation, with the caveat that automated instruments may not be appropriate everywhere. Cross-cutting features of the regional legacies, approaches, and programs can be summarized as follows:

(1) Each region is unique, and we cannot develop a one-size-fits-all-approach.
(2) At the same time, successful programs include strong buy-in and coordination with end-users and stakeholders, including citizen scientists.
(3) Technology is automating monitoring in many regional programs, but these measurements and models must be institutionalized to maintain continuity.
(4) Integrated modeling approaches that provide co-benefits for multiple resource monitoring efforts or are integrated into regional and national programs are the most stable in the long-term.

In order to improve existing HAB monitoring and prediction efforts, there is a critical requirement to continue to foster international cooperation and interdisciplinary research, to increase operational capabilities to capture HAB events in real-time, and to increase the spatial and vertical resolution of models. The projects highlighted in this community paper are all good examples of blended technology projects with public and private consortium members. As technologies continue to advance, it is essential that working groups and collaborative projects are established to facilitate effective interdisciplinary communications. Interaction with, and feedback from, stakeholders is essential for a successful HAB surveillance and forecasting system. The feedback loop ensures end-user information products are continually refined and developed as user needs increase and change with time. Finally, over the next 10 years, a continued long-term commitment and support from governing bodies at the local, regional, and international levels will play a significant role in determining if more robust automated HAB forecasting services of value are delivered (**Table 1**).

SCALING UP: FUTURE DIRECTIONS FOR GLOBAL OBSERVING OF HABS

A critical, strategic tool for addressing HABs as a global community is the common language that is forming in the Global Ocean Observing System (GOOS) around essential oceanographic variables (EOVs) and in the Group on Earth Observations (Pereira et al., 2013) around essential biodiversity variables (EBVs) (Navarro et al., 2017; Muller-Karger et al., 2018a,b). While more refinement of terms is needed, attaining a fundamental and universal lexicon of terms is relevant to the distribution, management, and discoverability of plankton datasets and HAB information. From there, a standardized set of indicators will lead to a more cohesive assessment of global trends and impacts from HABs and interacting environmental

TABLE 1 | Future needs of different sectors in the European Union (also found at www.coclime.eu/node/132).

Regulators	Industry	Scientists	Society
• Low cost monitoring programs • Appropriate legislation • Reliable traceability measures • Reliable and standardized international alert systems • Increased understanding of economic impacts (losses and gains)	• Reliable and consistent information from scientists • Rapid on-farm / in-water monitoring technologies • Long term forecasts • Mitigative measures • Multi trophic aquaculture and bio-control of HABs	• Integration across disciplines • Artificial neural networks and computer aided decision making • Continuity of skills • Building capacity and Training Improved • Standardized spatial measurements from remote multi-sensors • Cheap, operational high-quality data collecting *in situ* sensors • Increased sharing of transferable "Best" Practice(s) / methodologies	• Seafood Security • Seafood Safety • Thriving healthy marine ecosystems • Functional Foods • Employment from developing coastal economies • Clean seas • Low carbon

pressures, such as sea level rise, ocean acidification, and coastal hazards. Looking ahead to the next decade, policy directives will need to identify and describe the appropriate phytoplankton community and HAB-related ecosystem indicators that integrate across SDGs and are relevant to an effective early warning system.

GOOS recently organized a workshop to identify a common set of goals for implementing a global and sustainable, multi-disciplinary plankton observing capability (Miloslavich et al., 2018b). The central themes surrounding the workshop recommendations resonate with the case studies described in this paper: (1) communication with stakeholders, (2) accessibility of affordable, real-time automated imagers for *in situ* plankton detection and quantification, (3) and availability of standardized data sets that reside in major, global biodiversity and event databases, such as OBIS, the Harmful Algae Event Database (HAEDAT), and the Global Biodiversity Information Facility (GBIF) (Miloslavich et al., 2018a). The latter topic of data standardization, archive, and discoverability is woven into the regional HAB monitoring vignettes presented here, whereby stakeholder engagement and database management form a tight feedback loop. For a global HAB observing system that is dependent on globally defined SDG-level indicators to be fully operative, however, seemingly mundane issues such as data management "best practices" become ever more important. Indeed, ecological forecasting and trend analyses, such as those captured by Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assessments (Ferrier et al., 2016) or used to support a growing Blue Economy, strongly rely on the interoperability of geospatial data and compatibility across user interfaces for biogeographic and biodiversity data repositories.

RECOMMENDATIONS FOR A GLOBAL HAB OBSERVING SYSTEM

In an effort to encourage the development of an integrative global ocean observing system optimized for HABs and building on the GOOS framework for ocean observing (UNESCO, 2012), we contribute these specific objectives that are inspired by the regional case studies presented in this paper.

Deliver an observing system that is fit for purpose

- Advance and improve cost-effective and sustainable HAB forecast systems that address the HAB-risk warning requirements of key end-users at global and regional levels.
- Fill the essential need for sustained, and preferably automated, near real-time information from nearshore and offshore sites situated in HAB transport pathways to provide improved, advanced HAB warnings.
- Increase communication between regions to enable knowledge-sharing of best practices.

Apply a systems approach for sustained global ocean observing

- Incorporate available Earth Observations into monitoring and predictive efforts, including blended model-satellite products and data-assimilative model systems.
- Merge ecological knowledge and models with existing Earth System Modeling Frameworks to enhance end-to-end capabilities in forecasting and scenario-building.
- Work toward providing seasonal to decadal forecasts to allow governments to plan and adapt to a changing marine environment while ensuring coastal industries are supported and sustained in the years ahead.

Recognize and develop interfaces among all actors in the Framework for their mutual benefit

- Identify societal priorities with respect to the HAB problem, e.g., public health, food security, clean drinking water, aquaculture, sustainable fishing, tourism and recreation.
- Address critical stakeholder needs while striving to attain and sustain climate-quality data sets for scientific understanding of long-term trends in HABs.
- Build interoperable user interfaces such that complementary biological and environmental datasets can be accessed by user groups.

Provide the basis for and promote transformation of observational data organized in EOVs into information (syntheses, analyses, assessments, forecasts, projections, and scenarios) that serves a wide range of science and societal needs and enables good management of the human relationship with the ocean.

- Form programs with robust communication channels for stakeholders and partners.
- Support implementation of the recent calls for action by the UN 2010 SDGs to develop global indicators that remain relevant to early-warning systems at the regional scale.
- Design programs that leverage regional HAB observing systems to evaluate emerging technologies for EOVs and EBVs in order to support interregional technology comparisons and regional networks of observing capabilities.
- Facilitate dialogue on HABs within all relevant global initiatives, e.g., GOOS, GlobalHAB, Future Earth, GEO, and the International Ocean-Color Coordinating Group, to name just a few.
- Challenge policy-makers to incorporate goals for HAB mitigation that cut across SDG themes and promote maximal societal benefit.

AUTHOR CONTRIBUTIONS

CA contributed to the overall writing and framework of the manuscript, with significant contributions from EOR, CC, EB, RK, and JS. Regional contributions were written by DD and MM (Alaska), SM and JN (Pacific Northwest), CA and RK (California), BK and KH (Gulf of Mexico), JM (Gulf of Maine), SR and KP (Great Lakes), EB and JM (Caribbean Islands), EOR, CC, EB, and JS (European Union), and RK (Asia). All authors contributed to the manuscript revision and have read and approved the submitted abstract.

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frontiers in Marine Science

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From Observation to Information and Users: The Copernicus Marine Service Perspective

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The Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic reference information on the physical and biogeochemical ocean and sea-ice state for the global ocean and the European regional seas. CMEMS serves a wide range of users (more than 15,000 users are now registered to the service) and applications. Observations are a fundamental pillar of the CMEMS value-added chain that goes from observation to information and users. Observations are used by CMEMS Thematic Assembly Centres (TACs) to derive high-level data products and by CMEMS Monitoring and Forecasting Centres (MFCs) to validate and constrain their global and regional ocean analysis and forecasting systems. This paper presents an overview of CMEMS, its evolution, and how the value of *in situ* and satellite observations is increased through the generation of high-level products ready to be used by downstream applications and services. The complementary nature of satellite and *in situ* observations is highlighted.

Long-term perspectives for the development of CMEMS are described and implications for the evolution of the *in situ* and satellite observing systems are outlined. Results from Observing System Evaluations (OSEs) and Observing System Simulation Experiments (OSSEs) illustrate the high dependencies of CMEMS systems on observations. Finally future CMEMS requirements for both satellite and *in situ* observations are detailed.

Keywords: ocean, observing systems, satellite, *in situ*, data assimilation, services

INTRODUCTION

The Copernicus Marine Environment Monitoring Service (CMEMS) is one of the six pillar services of the EU (European Union) Copernicus programme. Mercator Ocean International was tasked in 2014 by the EU under a delegation agreement to implement the operational phase of the service from 2015 to 2021. The CMEMS provides regular and systematic reference information on the physical and biogeochemical ocean and sea-ice state for the global ocean and the European regional seas. This capacity encompasses the description of the current situation (analysis), the prediction of the situation 10 days ahead (forecast), and the provision of consistent retrospective data records (reprocessing and reanalysis). CMEMS provides a sustainable response to European user needs in four areas: (i) maritime safety, (ii) marine resources, (iii) coastal and marine environment, and (iv) weather, seasonal forecast and climate. A major objective of the CMEMS is to deliver and maintain a state-of-the-art European service responding to public and private intermediate user needs, and thus involving explicitly and transparently these users in the service delivery definition.

The CMEMS mission includes:

- ✓ Providing short-term forecasts and outlooks for marine conditions and, as appropriate, to downstream services for warnings of and/or rapid responses to extreme or hazardous events;
- ✓ Providing detailed descriptions of the ocean state to initialize coupled ocean/atmosphere models for predicting changes in the atmosphere/climate;
- ✓ Monitoring and reporting on past and present marine environmental conditions (physics and biogeochemistry), in particular, the response of the oceans to climate change and other stressors;
- ✓ Analyzing and interpreting changes and trends of the marine environment;
- ✓ Providing an easy, efficient, and timely information delivery service to users;
- ✓ Developing a communication and outreach plan and activities that allow European users to fully benefit from information and intelligence about the marine environment.

Observations are a fundamental pillar of the CMEMS value-added chain that extends from observation to information and users. Use of modeling and data assimilation is then an essential step for transforming sparse *in situ* and surface satellite observations into four dimensional ocean fields and forecasts (e.g., Bell et al., 2015). Data assimilation allows dynamical interpolation of observations, taking into account the complementarities between the different types of observations, and allows derivation of parameters that are not directly observed. High spatial and temporal resolution ocean fields, consistent with observations and model dynamics and ocean forecasts, are thus derived. Such a science-based and state-of-the-art approach is required to best serve applications and users.

The ocean observing system is highly dependent on international cooperation and the international coordination from the Global Ocean Observing System (GOOS) and the Committee for Earth Observation Satellites (CEOS) is essential to CMEMS. CMEMS also benefits from and contributes to international cooperation and coordination on modeling and data assimilation through the GODAE OceanView/Ocean Predict programme and users and applications through the Group of Earth Observation (GEO) Blue Planet initiative.

The paper provides an overview of *in situ* and satellite observations that are used by CMEMS and details present and future requirements. The objective is to detail how integrated systems, such as CMEMS, critically depend on observations and provide the reader with long-term perspectives for the development of CMEMS and implications for the evolution of the *in situ* and satellite observing systems. This paper is organized as follows. An overview of CMEMS products, services, and users is given in section CMEMS Architecture, Products, and Users, while section CMEMS Service Evolution details over-arching goals and associated actions planned for the evolution of the service. To quantify the high dependencies of CMEMS systems on observations, results from OSEs (Observing System Evaluations) and OSSEs (Observing System Simulation Experiments) are presented in section Role and Impact of observations for the Copernicus Marine Service. Initial requirements, status and future requirements for satellite and *in situ* observations are discussed in sections Satellite Observations Used by the Copernicus Marine Service: Status and Requirements and *In situ* Observations Used by the Copernicus Marine Service: Status and Gaps, respectively. Main conclusions are given in section Conclusion.

CMEMS ARCHITECTURE, PRODUCTS, AND USERS

Architecture

The backbone of the CMEMS relies on a distributed architecture of production centers for observations (Thematic Assembly Centres—TACs), modeling/assimilation (Monitoring and Forecasting Centres—MFCs) and a Central Information System (CIS) (**Figure 1**); it includes:

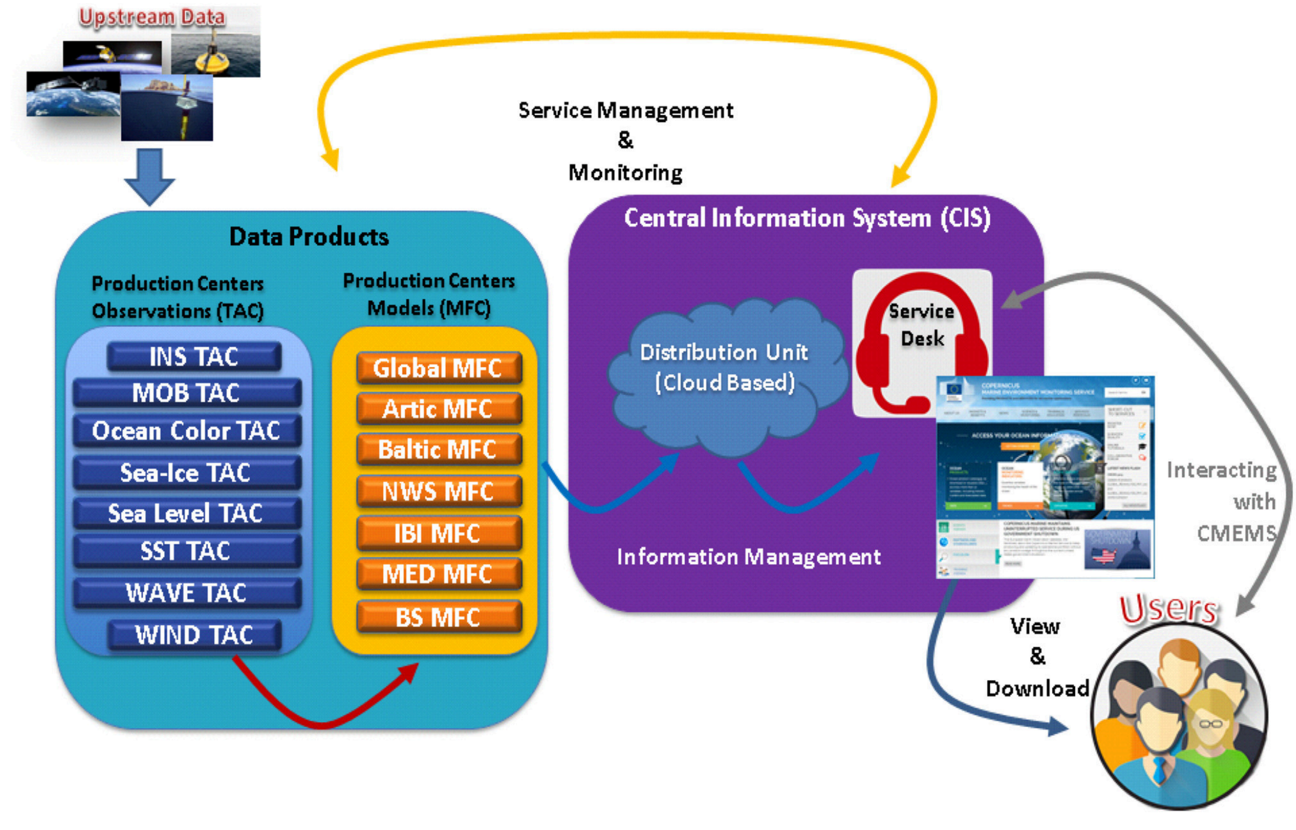

FIGURE 1 | CMEMS Architecture.

- Eight TACs, six satellite TACs organized by ocean variables (sea-surface topography, ocean color, sea-surface temperature, sea-ice, winds and waves), one for *in situ* observations and one multi-observation TAC (that merges different *in situ* and satellite data to elaborate high-level products). These production centers gather observation data from *in situ* networks [e.g., the Global Ocean Observing System (GOOS), the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), and the European Global Ocean Observing System (EuroGOOS) and from the Copernicus satellite component, through the European Space Agency (ESA) and the European organization for the exploitation of Meteorological Satellite (EUMETSAT)]. TACs generate validated data sets directly useable for assimilation in models (MFCs) and derive high-level products (i.e., gridded multi-sensor products) directly useable for downstream applications.
- Seven MFCs, distributed according to the marine area covered (Global Ocean, Arctic Ocean, Baltic Sea, North Atlantic North West European Shelf, North Atlantic Iberia-Biscay-Ireland area, Mediterranean Sea and Black Sea), that generate model-based products on the ocean physical state and biogeochemical characteristics, including forecasts, hindcasts and reanalyses.
- A CIS, encompassing the management and organization of CMEMS information and products. A single catalog (global and European coverage) is offered to users. The CIS allows searching, viewing, downloading products and monitoring of the system. A manned service desk provides a network of technical and marine experts to support users.

Products

CMEMS products are based on state-of-the-art data processing and advanced modeling and data assimilation techniques. The product uncertainties are assessed through rigorous internationally recognized quality assessment methods (e.g., Hernandez et al., 2015). CMEMS today provides about 160 different products for observations and model outputs (CMEMS catalog at http://marine.copernicus.eu) covering ocean physics (temperature, salinity, sea level, currents, waves), sea-ice (concentration, thickness, drift) and biogeochemistry (chl-a, oxygen, pH, nutrients). Modeling and data assimilation products have a resolution of 1/12° for the global scale and from 1/24° to 1/72° for the regional applications. The CMEMS CIS and its service desk provide an easy, efficient and timely access to CMEMS data and products and related information.

CMEMS publishes an annual Ocean State Report (Von Schuckmann et al., 2017, 2018) for the scientific community, as well as for policy and decision-makers. It provides information on the state of the global ocean and European regional seas and how they have changed over the recent past. The Ocean State Reports rely on the unique capability and expertise that CMEMS gathers in Europe to monitor, assess and report on past and present marine environmental conditions and to analyse and interpret changes and trends in the marine environment. Based on Ocean State Report results, CMEMS produces Ocean Monitoring Indicators (OMIs) that are used to monitor the main changes and trends in the marine environment over the past 25 years. The CMEMS data and products allow comprehensive monitoring of the global ocean and European seas. CMEMS Ocean State Reports and associated OMIs go one step further by developing science-based assessments of the state and health of our oceans and seas.

Data Access

All CMEMS products (NetCDF format) are freely accessible through a single internet interface (http://marine.copernicus.eu/getting-started/).

The interactive catalog (http://marine.copernicus.eu/services-portfolio/access-to-products/) allows users to select products according to geographical area, parameter, time span, and vertical coverage. Users can also select a product by using a key-word search. Once a product has been selected, the user can view it without registration.

Once a product has been selected, CMEMS offers three different authenticated download mechanisms:

- Subsetter (HTTP protocol, subset the files) to extract and download only a part of a product (per area, per variable, for a period of time, some depths).
- Direct Get File (HTTP protocol) to download large dataset (according to a period of time).
- CMEMS FTP (standard FTP protocol).

Access to the catalog and instructions to discover, search and download CMEMS products are detailed in a dedicated "Tutorial Section" (http://marine.copernicus.eu/training/online-tutorials/).

Users

CMEMS provides a core/generic service targeting downstream service providers (intermediate users) and serving a wide range of users and applications. Four key application areas have been identified:

- Maritime Safety: marine operations, sea-ice forecasting, incident response (e.g., oil-spill), ship routing, search and rescue, flood prevention and offshore industries and operations.
- Marine Resources: sustainable management of living marine resources, including fisheries and aquaculture. The primary goals of fishery management are ecosystem services, as well as maximum sustainable yield and rebuilding overexploited stocks. Aquaculture management bodies provide advice on the assessment of the multitrophic productivity and on the environmental impact of marine farming.
- Marine and coastal environment: monitoring and understanding good environmental status (see the European Marine Strategy Framework Directive), sustainable tourism and aquaculture, protection of the coasts against erosion and land-based sources of pollution, as well as human and ecosystem health. The development of effective Integrated Coastal Zone Management concepts and decision-making support systems are also included.
- Weather, seasonal forecasting and climate: quality-controlled marine information on a daily basis, as well as long time series of reprocessed data and reanalyses.

CMEMS is also important to make progress toward assessing the impact of ocean physical and biogeochemical changes on biology and biodiversity.

Details of CMEMS benefit areas and a series of use cases (>150) are available at http://marine.copernicus.eu/markets/.

The CMEMS service desk regularly monitors the number and types of users, the statistics on downloaded products and user satisfaction (**Figure 2**). More than 15,000 users are now registered with the service and there has been a steady increase in the uptake of the service over the past couple of years. CMEMS users are distributed across its four benefit areas. More than half of CMEMS users and 25% of the number of downloads come from research organizations. Public sector applications (e.g., policy, environmental monitoring, and marine safety) represent 18% of the users and 33% of the number of downloads. Private sector applications account for 13% of the users and 35% of the number of downloads. Users access model-based and observation products equally. The same holds for real-time (observations, models) and delayed mode (reprocessed data sets and reanalyses) products. The most frequently downloaded products are the real-time global analyses and forecasts, followed by reprocessed and real-time gridded sea-level maps. Real-time global gridded sea-surface temperature (SST), global ocean reanalyses and Mediterranean Sea regional analyses and forecasts are the next group of most-downloaded products.

CMEMS SERVICE EVOLUTION

Strategy

CMEMS evolves based on requirements from its users, considering both existing and future needs, and the need to maintain competitiveness with respect to international players. CMEMS evolution responds to new science and technology (e.g., modeling and assimilation developments and data processing technologies) and opportunities emerging from satellite and *in situ* observations, thus strongly linking CMEMS evolution to that of the *in situ* and satellite observing systems.

The CMEMS Service Evolution high-level strategy and its associated Research and Development (R&D) priorities (Mercator Ocean, 2016; CMEMS STAC, 2017) introduce a set of overarching goals and associated actions and R&D priorities for evolving the service from its initial state toward a mature, state-of-the-art, leading and innovative Copernicus Service.

Drivers: Societal Needs and Blue Growth

The need to monitor and forecast the oceans has never been so high on the political agenda: (1) the Sustainable Development Goal 14, "*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*" is firmly on the 2030 agenda of the United Nations; (2) the Intergovernmental

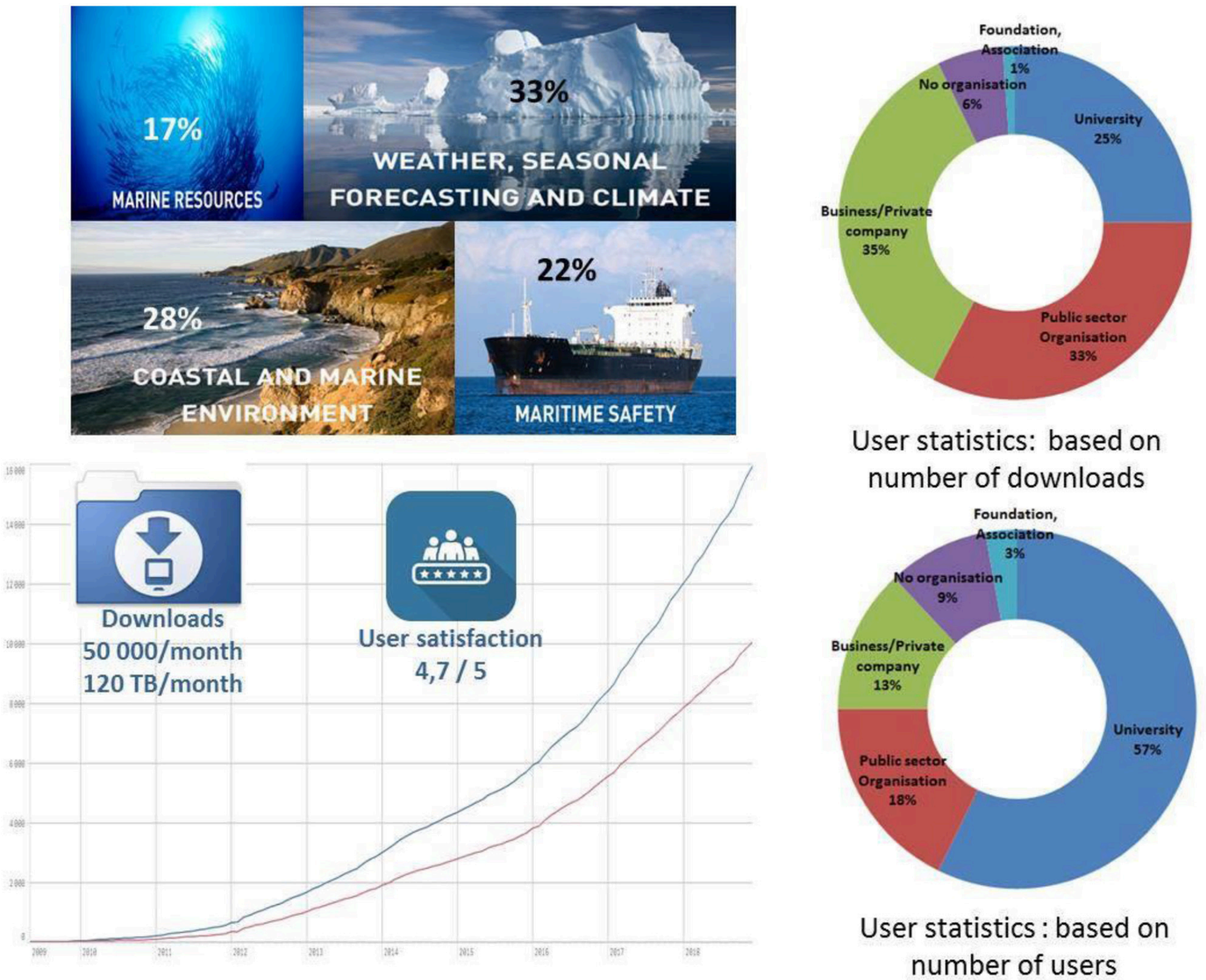

FIGURE 2 | CMEMS Service Monitoring statistics. Number of registered users (blue) and active users (i.e., those who have downloaded data; lower left; red). User statistics (average over 2018) per benefit areas (upper left) and per user types, based on number of users (upper right) and number of downloads (lower right). User satisfaction figure, number of downloads per month (1 download = 1 user x 1 dataset) and volume of downloads per month are also given.

Panel on Climate Change decided to prepare a report "The Ocean and Cryosphere in a Changing Climate"; and (3) the G7 science ministers have set up a special initiative on the future of the ocean and its seas. Monitoring and forecasting are essential for sustainable management of the ocean and its resources, which are under pressure due to the effects of climate change and other human activities (e.g., fishing, pollution, mining), as well as for developing the blue economy. It is equally important in order to understand and predict how our climate is evolving. In 2010, the ocean economy represented USD 1.5 trillion in value (OECD, 2016). By 2030, conservative assessment estimates that ocean economy will grow to more than USD 3 trillion, much of which will rely on coastal tourism, offshore oil and gas and port activities. Marine aquaculture will grow at an annual rate of 5.7% between 2010 and 2030. The blue economy growth will increase stress on ocean resources and marine spatial planning, especially in exclusive economic zones. The need for much better management of the oceans, relying on comprehensive ocean observing, monitoring, forecasting and assessment activities, is the main driver for CMEMS and its evolution.

Gathering User Requirements and Translating Them Into Future Service Solutions

CMEMS is a user-driven service with user requirements being regularly gathered by Mercator Ocean International and its CMEMS partners through user workshops (regional and thematic), training sessions, questionnaires and regular user interactions with the CMEMS service desk. Initially, the main requirements from users included the need for better spatial resolution, improved quality assessment and the addition of wave products (both observations and model-based products) into the service catalog.

User requirements drive the evolution of CMEMS service, which, in turn, leads to revised specifications for satellite and *in situ* observations. User requirements (e.g., knowledge of the ocean currents at 1-km resolution) do not translate directly into satellite or *in situ* observation requirements. User requirements must go through the service value-added chain, taking into account, in particular, the complementary nature of satellite and *in situ* observations and the role of modeling and data assimilation. CMEMS requirements for future observations are thus based on an analysis of the observations required and most important for improving/constraining future CMEMS products and services.

Service Evolution

CMEMS service evolution and associated R&D activities are essential in order to respond to user needs, maintain state-of-the-art systems and to benefit from improved observing systems and scientific advances in processing, validation methodologies, modeling and data assimilation. As described in Le Traon et al. (2017a), important R&D advances have been achieved during CMEMS Phase 1 (April 2015-April 2018) and a significantly improved service is now provided to the users, including wave products, improved model resolution, wave/circulation coupling, better use of existing satellite and *in situ* observations, uptake of Sentinel-1 (S-1) (sea-ice coverage, ocean waves) and Sentinel-3 (S-3) (altimetry, sea-surface temperature, ocean color) data, longer time series of reprocessed *in situ* and satellite data and ocean reanalyses, improved and more homogenized product quality assessments, ocean monitoring indicators and ocean state reports.

In April 2018, CMEMS entered its Phase II (April 2018-April 2021). During this time, the following improvements or evolutions are planned:

- Improving product quality and product quality assessment.
- Improved horizontal and vertical model resolution.
- Increasing the number of MFCs with explicit representation of tides.
- Wave/circulation coupling to better represent upper-ocean dynamics (e.g., currents).
- Improved data assimilation methods (e.g., ensemble methods) and the assimilation of new types of data (e.g., sea-ice thickness).
- Improved CMEMS biogeochemical (BGC) products (observations and model-based), with the assimilation of ocean color satellite observations in all BGC models and the progressive assimilation of BGC Argo data.
- New observation products [in particular, surface currents from High Frequency (HF) radars; sea-ice thickness from Cryosat-2, SMOS and Sentinel-3; partial pressure of CO_2 (pCO2) and acidity (pH) from *in situ* observations].
- Better addressing requirements of coastal users. Improved satellite products (e.g., high-resolution ocean color) will be proposed and stronger links with downstream coastal modeling systems will be set up.
- In parallel, the Copernicus Data and Information Access Services (DIAS) platforms (e.g., wekeo.eu) will allow the development of new services by providing an integrated access to data and products from all Sentinel satellites and Copernicus Services. Cloud-based processing capabilities will be provided so that users can develop and execute their own applications.

In the longer term, CMEMS will need to significantly evolve in order to monitor and forecast the ocean at finer scale and to improve the monitoring of the coastal zone. In the post-2025 time period, CMEMS model resolutions will increase by a factor of at least three (e.g., global 1/36°, regional 1/108°) compared to the present, and more-advanced data assimilation methods will be available. The objective will be to characterize, at fine scale, the upper-ocean dynamics to improve, in particular, our ability to describe and forecast the ocean currents and provide better boundary conditions for very-high-resolution coastal models. This enhanced resolution is essential for key applications, such as maritime safety, maritime transport, search and rescue, fish egg and larvae drift modeling, riverine influence in the coastal environment, pollution monitoring and offshore operations. Fine-resolution modeling also poses strong challenges for the evolution of satellite (e.g., wide-swath altimetry) and *in situ* (e.g., high-resolution coastal observations) observing system evolution.

CMEMS must also improve its ability to monitor and forecast the BGC state of the ocean (e.g., ocean carbon uptake, acidification, de-oxygenation, eutrophication, water quality, biological productivity). Improved BGC products are required for the Marine Strategy Framework Directive (MSFD), guiding decisions and actions by governments and industry, and supporting knowledge-based management of marine resources (fishery, aquaculture). CMEMS offer is critically dependent on major improvements in the "green" component of the observing system, such as advanced satellite derived products, dedicated algorithms, and innovative *in situ* technologies (e.g., BGC Argo, Gliders, FerryBoxes, and Continuous Plankton Recorders).

ROLE AND IMPACT OF OBSERVATIONS FOR THE COPERNICUS MARINE SERVICE

The Role of Observations

The quality of CMEMS products is highly dependent on the availability of upstream *in situ* and satellite observations. Observations are used both by CMEMS TACs to create data products, and by CMEMS MFCs to validate and constrain their global and regional ocean analysis and forecasting systems. CMEMS critically depends on the near-real-time availability of high-resolution satellite data. *In situ* data are of paramount importance for CMEMS because they provide information about the ocean interior which cannot be observed from space. *In situ* observations also can locally sample high-frequency and high-resolution ocean processes, in particular, in the coastal zone that are essential for model and satellite validation activities.

The outstanding development of the Copernicus Sentinel missions has already had a major impact on CMEMS (Le Traon et al., 2017a). The impact will be even greater when the Sentinel constellations are fully implemented. CMEMS systems are, in particular, highly dependent on the status of the altimeter constellation. There is a clear degradation of analysis and forecast quality when reducing the number of assimilated altimeters. Sea-ice products and services have been strongly improved, thanks to the Sentinel-1 A/B constellation; however, they are also very dependent on third-party passive microwave missions. Ocean color and SST data from Sentinel-3 improved the quality of CMEMS ocean color and SST products. Sentinel-2 is not yet integrated into CMEMS products, but already demonstrated high potential for coastal zone monitoring. *In situ* observations also play a critical role within CMEMS. The Argo array of profiling floats has, in particular, a major impact on the quality of CMEMS global and regional analyses and forecasts (e.g., Turpin et al., 2016; Le Traon et al., 2017a).

Based on CMEMS Phase I activities, we now have a more refined understanding on the impact and utility of observing systems for the Copernicus Marine Service. The impact of present and future observations can be quantified and more precise recommendations for the observing system evolution can be derived. These assessments are described in sections Assessing the Impact of Present and Future Observations and Altimeter Constellation along with background information needed to revise/update CMEMS observation requirements provided in sections Satellite Observations Used by the Copernicus Marine Service: Status and Requirements and *In situ* Observations Used by the Copernicus Marine Service: Status and Gaps.

Assessing the Impact of Present and Future Observations

Ocean forecasting systems have a high dependency on observation availability and quality. Observation impact studies are required to:

- verify that observation information is "optimally" used in the analysis step and improve the assimilation components,
- quantify the impact of the present observation network on ocean analyses and forecasts,
- demonstrate the value of an observation network for operational ocean analysis and forecasts,
- help define and test new mission concepts, from an integrated system perspective involving satellite and *in situ* observations and numerical models.

Observation impact monitoring is part of CMEMS regular activities. This is done through OSEs and OSSEs (Fujii et al., this issue). By withholding observations, OSEs assess the impact of an existing data set on the performance of a modeling and data assimilation system (e.g., Lea et al., 2014). OSSEs help in designing future observing systems, evaluating their different configurations, exploring their potential impact, and performing preparatory data assimilation work. In an OSSE, one model is used to perform a "truth" run to produce synthetic observations for assimilation into the test model. The test model's performance is evaluated by comparing it against the truth run. OSSEs need to be calibrated with OSEs to ensure that results are meaningful (Hoffman and Atlas, 2016).

OSSEs and OSEs require significant computer infrastructure to run research versions of operational systems. Alternative and complementary approaches exist (Fujii et al., in review). The computation of Degrees of Freedom of the System (DFS) (Cardinali et al., 2004; Oke et al., 2015) allows, in particular, monitoring of the relative impact of observations on analyses. The DFS represent the equivalent number of independent observations that constrain the model analysis at the observation point. Comparing the DFS with the number of observations indicates the information content. Computation of DFS is simple in theory, but the practical implementation depends on the data assimilation scheme. DFS monitoring is progressively being implemented in the CMEMS MFCs and TACs. Even though the DFS values inherently have no physical meaning, providing them for each assimilation cycle has various practical uses:

- It serves as an internal diagnostic to verify that the relative impact of each assimilated data type or subset is balanced: no individual data stream is out-competing the other data sources.
- It provides a no-cost indication of how changes in upstream data (typically their frequency, location or accuracy) affect the relative balance between assimilated datasets.
- Changes of model settings can be similarly assessed.
- It provides a convenient way to assess the potential impact of planned missions, for which the data is not yet available, but the orbits, repeat cycles and the measurement uncertainties are known to some degree.

CMEMS has also developed multi-observations ocean products and systems based on observations (satellite and *in situ*) and state-of-the-art statistical data fusion techniques. They cover the physical and biogeochemical states of the ocean, at the surface and at depth. OSEs/OSSEs based on statistical data fusion techniques are lighter and complementary approaches to studies based on modeling and data assimilation systems. OSEs were used, for example, to evaluate the synergic use of satellite observation in improving the accuracy and resolution of observational products, such as currents (e.g., Rio et al., 2016; Rio and Santoleri, 2018) or salinity (e.g.,Buongiorno Nardelli, 2012).

Synthesis of OSE/OSSE Results

Altimeter Constellation

Sea-level multi-mission altimeter data sets are very sensitive to the altimeter constellation (in terms of the number of satellites and their orbital configuration). Historically, OSEs and OSSEs have been used in altimetry to measure or predict the impact of a constellation (e.g., Le Traon and Dibarboure, 1999). In the last decade, due to the increase of the number of altimetry missions, numerous studies have been performed. The first objective was to monitor the quality of the product as a function of the constellation. Dibarboure et al. (2011) quantified the higher level of Eddy Kinetic Energy observed with four satellites compared to two satellites. Then, with the aging of Jason-1, Jason-2 and Altika, the various scenarios for their end of life needed to be analyzed (e.g., Dibarboure et al., 2012, 2018). Several analyses also were performed to find the best compromise for the orbits of Sentinel-3B and D to give to the Sentinel-3 constellation the capacity to

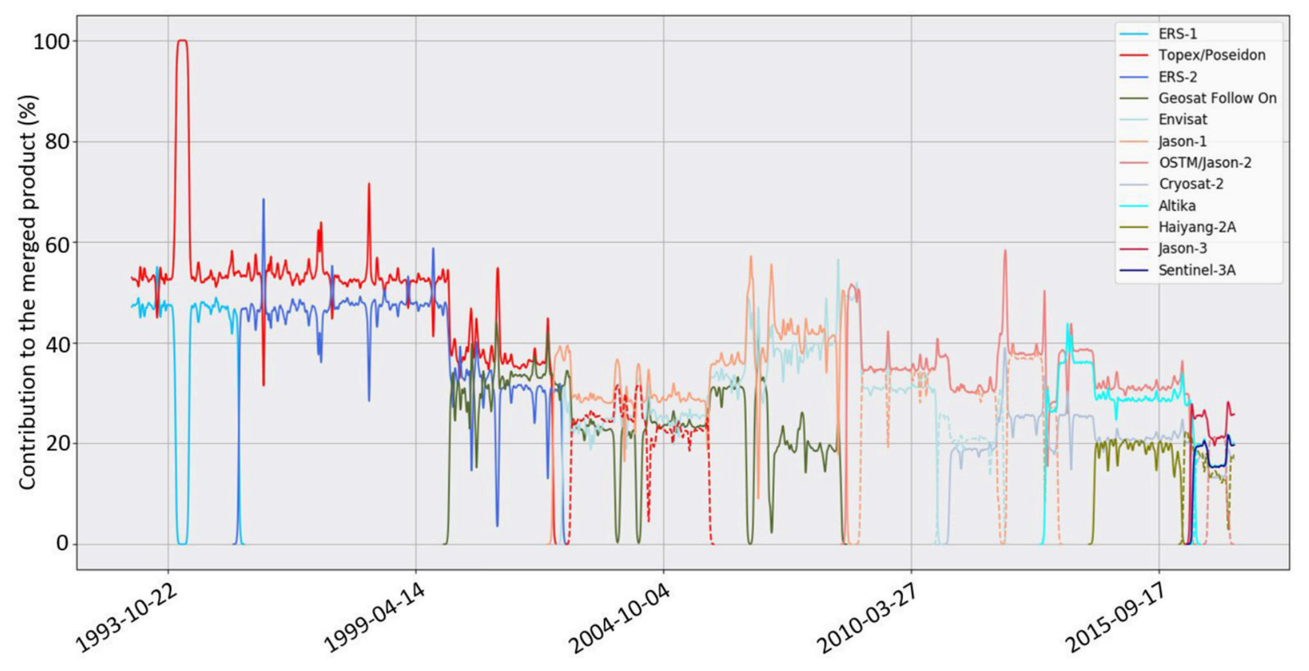

FIGURE 3 | Relative contribution (in percent) of each altimeter mission in the CMEMS multi-mission altimeter maps. Results are derived from a Degrees of Freedom of the System analysis. The top-right legend details the name of the altimeter missions in chronological order. In several cases, when the orbit configuration changes (e.g., management at the end of life of the mission) the mission contribution is represented by a dashed line.

monitor mesoscale variability much better than initially planned. Finally OSEs/OSSEs are needed to optimize future constellations (planned for the 2020/2030 time frame) and assess the potential of future altimetry missions (e.g., Pujol et al., 2012). **Figure 3** gives an overview of all the configuration change for past 25 years. It shows the relative contribution (in percent) of each mission in the CMEMS multi-altimeter maps. This contribution is derived from a DFS analysis computed as part of the offline production chain of the CMEMS Sea Level TAC.

CMEMS modeling and data assimilation systems highly depend on the status of the altimeter constellation (Le Traon et al., 2017b). Both OSEs (e.g., Hamon et al., in press) and OSSEs (e.g., Verrier et al., 2017) demonstrate the major contribution of altimetry. At least three and preferably four altimeters are required to constrain modeling and data assimilation systems (**Figure 4**). This is particularly true with high-resolution data assimilation systems. A new generation of nadir altimeters now provides enhanced capability, thanks to a Synthetic Aperture Radar (SAR) mode that reduces measurement noise (Boy et al., 2017; Heslop et al., 2017). A first assessment of the impact of SAR mode altimetry on ocean analysis and forecasting was carried out using OSSEs with the global Mercator Ocean high-resolution 1/12° system (Verrier et al., 2018). Compared to conventional altimetry, a constellation of three SAR altimeters reduces Sea Surface Height (SSH) variance errors for both analyses and forecasts by about 20% in western boundary currents, suggesting that use of SAR multiple altimeter missions with high-resolution models will improve the capability of the ocean analysis and forecasting systems in the near future.

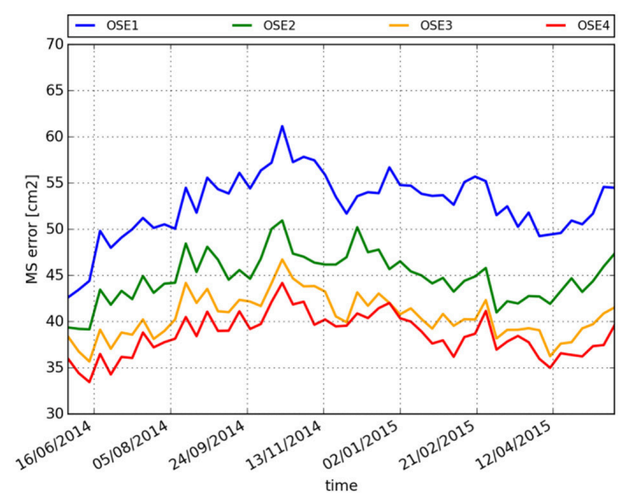

FIGURE 4 | Time series of Sea Surface Height (SSH) forecasts Mean Squared (MS) error (cm^2) for different Observing System Experiments (OSEs) assimilating 1, 2, 3, and 4 altimeters.

Accurate knowledge of the Mean Dynamic Topography (MDT) is a fundamental element for assimilation into operational ocean forecasting systems (e.g., Le Traon et al., 2017b). Thanks to the inputs of altimetric, *in situ* data and gravimetric missions (GRACE and GOCE satellite missions) data, MDTs are regularly updated (Rio et al., 2011, 2014), leading to considerable improvements in both forecasts and analyses.

Hamon et al. (in press) showed that, in terms of impact on SSH, assimilating an updated release of the MDT is comparable to assimilating a fourth altimeter. Due to steric adjustments, temperature and salinity biases in the top-2,000 m-depth layer are also reduced.

Wide-Swath Altimetry

Mercator Ocean has performed initial OSSEs for Surface Water Ocean Topography (SWOT) mission using a 1/12° regional model of the IBI region that includes tidal forcing (Benkiran, personal communication). The truth run was derived from a 1/36° model run over the same region. SWOT errors were derived using the NASA-JPL SWOT Simulator, taking into account only white-noise error from the Ka-band radar interferometer instrument (Karin). This first study demonstrated the feasibility of assimilating SWOT data in Mercator Ocean high-resolution models. It also quantified how SWOT should better constrain ocean models, compared to conventional nadir altimeters. Compared to three nadir altimeters, SWOT combined with three nadir altimeters (post-2021 situation) should allow a reduction of 5-day sea-level analysis and forecast errors by about 45 and 30%, respectively. The system is also able to sustain the appropriate level of mesoscale activity, in spite of the SWOT revisit time (21 days).

The impact of a constellation of two wide-swath altimetry missions was investigated with the same IBI data assimilation system (Bonaduce et al., 2018). This assessment was carried out as part of an ESA study on the potential role of wide-swath altimetry for the long-term (post 2030) evolution of the Copernicus satellite component. In that study, noise-level requirements were less stringent than for the SWOT mission (by a factor of two to four compared to Karin/SWOT instrument). Considering a constellation of three nadir and two wide-swath altimeters, the ocean analysis error was reduced up to 50%, with respect to conventional altimeters (**Figure 5**). The accuracy of the analysis also is more stable in time with the reduced revisit time provided by two large swath altimeters, compared to only one.

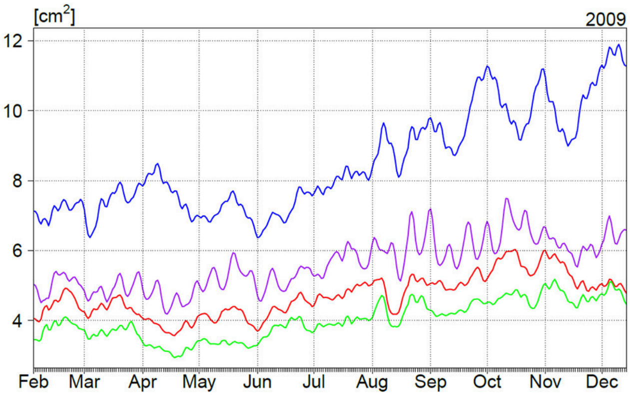

FIGURE 5 | Impact of a constellation of two wide-swath altimetry missions in a Northeast regional data assimilation system, for different constellation configurations and different instrumental error budgets (with reference to the SWOT Karin instrument) (Bonaduce et al., 2018). In that study, noise level requirements were less stringent as for Karin instrument. OSSE1= 3 altimeters (SAR mode) (blue), OSSE2 = OSSE1 + Wide Swath (4 times Karin error) (violet), OSSE3 = OSSE1 + 2 Wide Swath (4 times Karin error) (red), OSSE4 = OSSE1 + 2 Wide Swath (2 times Karin error) (green). Units are in cm^2. Results are given from February to December 2009.

Argo and Its Extensions

The global Argo array has successfully provided large-scale ocean temperature and salinity estimates in the upper-2,000 dbar for more than 15 years, complementing satellite observations in the global ocean observing system (Riser et al., 2016). It is clearly identified as a central piece of operational oceanography (e.g., Le Traon, 2013). Several impact studies have been conducted within the Euro-Argo Improvements for the Copernicus Marine Service (E-AIMS) project to evaluate and quantify how the existing Argo array constrains ocean analysis and forecasting systems. These studies showed that the existing Argo network has strong impacts on upper-ocean representation (Turpin et al., 2016). Argo also has a strong impact at the regional scale for both the Mediterranean and Black Seas (e.g., Grayek et al., 2015; Sánchez-Román et al., 2017).

The future evolution of Argo is mainly through the extension and improvement in the regional and polar seas, into the deep ocean, in the western boundary currents and through adding biogeochemical measurements (Roemmich et al., in review). As part of the European Union's Horizon 2020 (H2020) AtlantOS project (https://www.atlantos-h2020.eu/), four European forecasting centers have coordinated efforts to perform multi-system OSSE experiments for Argo and its extensions (Gasparin et al., 2019). It has been shown that doubling the number of Argo floats in the western boundary currents and along the equator would generally improve both temperature and salinity representation. Implementation of a deep Argo array (1 float every 5 × 5 square, monthly) that samples to 4,000 dbar, or to bottom, would remove temperature and salinity biases in the deep ocean basins (**Figure 6**). Further investigations have demonstrated that such a deep array would (i) improve the representation of the deep circulation (e.g., western boundary currents), and (ii) provide robust estimates of deep ocean climatic signals (Gasparin, personal communication), which are of critical interest for CMEMS reanalyses. In addition to these experiments for physical parameters, numerical experiments have shown that assimilating BGC-Argo data complements surface ocean color data by improving model estimates of oxygen, nutrients, carbon and chlorophyll throughout the water column (Wood et al., 2018).

The impact of assimilating BGC Argo data jointly with satellite chlorophyll observations in the Mediterranean Sea has been analyzed as part of the CMEMS Service Evolution MASSIMILI project (Cossarini et al., 2019). Results show that, when a dataset is assimilated, the model performance computed on the same dataset improves on the order of 50–70%. However, the joint assimilation experiments are not always providing the overall best results because of some inconsistencies between the observation datasets. Chlorophyll vertical dynamics are significantly improved only when the BGC-Argo data are assimilated. Satellite assimilation can generate negative impacts, highlighting a potential limit to propagating surface information into vertical dimension through statistical operators.

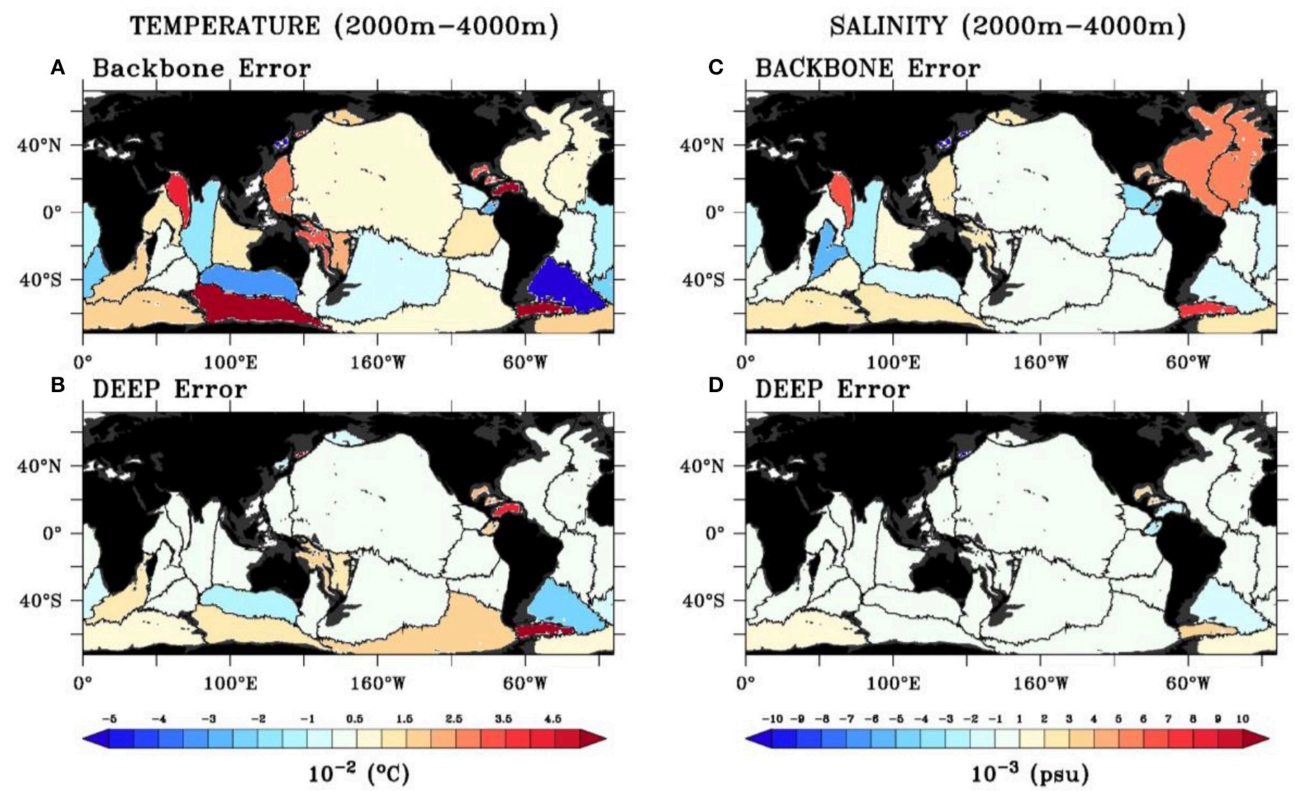

FIGURE 6 | Basin-averaged error in the layer 2000–4000 m, for **(A,B)** temperature and **(C,D)** salinity from the Backbone (assimilation of altimetry, core-Argo, XBT, moorings) and the Deep (Backbone+deep-Argo) experiments.

Sea-Surface Salinity

Several satellite missions (SMOS, SMAP and Aquarius) were launched in recent years to observe global Sea-Surface Salinity (SSS) from space. CMEMS ocean forecasting systems rely on sub-surface salinity observations, mainly from Argo floats, to constrain the SSS. Model and *in situ* SSS data comparison shows model uncertainties to be <0.1/0.2 pss in most of the ocean regions, with larger errors found in ocean regions controlled by large river runoffs (e.g., Amazon plume, Gulf of Mexico) and in the tropical oceans (e.g., Lellouche et al., 2018). SSS observations from space, even if still suffering from large-scale biases, provide valuable information (e.g., Reul et al., 2013; Martin et al., 2019). CMEMS already provides SSS maps based on a combination of *in situ* and SMOS data (Droghei et al., 2018). In the framework of the ESA SMOS Nino 2015 project, the impact of satellite SSS data assimilation was assessed with the Met Office and Mercator Ocean global ocean analysis and forecasting systems (Tranchant et al., 2018; Martin et al., 2019). Results show that satellite SSS data assimilation can constrain model forecasts without introducing incoherent information compared to the other assimilated observations. A bias correction still has to be applied within the assimilation process, even if "debiased" SSS data products are assimilated. Further progress on satellite SSS retrievals is required to enhance the benefit of satellite SSS data assimilation, particularly when close to the coasts and at high latitudes.

Sea-Ice Observations

Numerous OSSEs have been carried out for sea-ice remote sensing, in particular for sea-ice thickness products from CryoSat-2 (Lisæter et al., 2007; Blockley and Peterson, 2018), as well as for thin ice thickness from SMOS (Yang et al., 2014; Xie et al., 2016) and both satellites together (Allard et al., 2018; Mu et al., 2018; Xie et al., 2018). Assimilation of combined CryoSat-2 and SMOS sea-ice thickness products in the Arctic MFC has a very positive impact by reducing sea-ice thickness errors by 12 to 24% (Xie et al., 2018). Improvements in sea-ice concentrations data have also been assessed by OSSEs (Posey et al., 2015). Weighting the value from different observation types has been done by adjoint modeling (Kaminski et al., 2018). The assimilation of sea-ice drift has been less successful, so far, partly because of the short model memory of sea-ice drift and partly because of sea-ice models deficiencies (Stark et al., 2008; Sakov et al., 2012). More details are given in the Swart et al. (in review) paper on Polar Ocean Observations.

Surface Carbon Observations

OSSEs have also been conducted in the framework of the AtlantOS project for surface ocean carbon products (pCO2) using CMEMS multi-observation platform for ocean carbon and a statistical model (Denvil-Sommer et al., 2018). The aim of the work was to identify an optimal observational network for pCO2 for the Atlantic Ocean using simulated observations and output from the NEMO-PISCES model. Tests highlighted the need for data in the South Atlantic Ocean, the Surface Ocean CO2 Atlas (SOCAT) having sparse coverage in the Southern Hemisphere.

The main results (Sommer et al., 2018) show that the combination of (1) the SOCAT data base (integrating data from multiple platforms) with (2) a network of BGC Argo floats at around one quarter of current physical Argo resolution, and (3) existing moorings provides an optimal solution, which probably could be implemented with the least cost.

The network could be further improved by instrumenting Baffin Bay, the Labrador Sea, and the Norwegian Sea, as well as regions along the coast of Africa (10°N to 20°S) with moorings or additional BGC-Argo floats.

Waves

Satellite wave observations are used to improve the wave products provided by CMEMS MFCs, ultimately yielding better surface fluxes needed for coupling with ocean circulation models. Currently, significant wave heights (SWH) from five altimeters (Jason-2 and 3, Saral/Altika, Cryosat-2 and Sentinel-3A) are routinely assimilated every 3 h in the global CMEMS MFC wave system, leading to very accurate integrated wave parameters. For example, the normalized scatter index (given by the ratio between the standard deviation of the difference between modeled and observed parameter and the mean of the observed parameter) of SWH is below 9% in high and intermediate latitudes and is even > 8% for tropical regions (Aouf et al., 2018a).

The assimilation of satellite wave data in wave models is the most efficient way to correct the uncertainties related to the wind forcing, in particular for storm cases. The case of Campbell Island, south of New Zealand is highlighted. Significant wave heights of more than 12 m were observed there by altimeters from 7 to 10 May 2018 (**Figure 7A**). At 12:00 (UTC) during the storm on 8 May 2018, the Metocean Solutions buoy at Campbell Island recorded the peak of SWH of 14 m, which clearly agrees with the analysis provided by the global CMEMS-MFC (**Figure 7B**).

At the regional level, the impact of assimilating satellite observations on the Med-Wave system has been evaluated considering the Med-Waves-V4 system, assimilating along-track significant wave height observations from Jason-2 and Saral satellites at 3-hourly intervals, vs. the Med-Waves-V3.2 system without data assimilation (Ravdas et al., 2018). Data assimilation improves results along satellite tracks, as well as at the great majority of the wave buoy locations.

Satellite wave data concern not only altimeter significant wave heights, but also directional wave spectra provided by Synthetic Aperture Radar (SAR). Because of the SAR's inability to image short and steep waves (with a wavelength less than about 200 m) in the azimuth direction due to their incoherent nature, SAR wave measurements are often referred to as swell measurements (hereinafter referred to as "swell spectra"). SAR swell spectra are currently provided by two Copernicus satellites, Sentinel-1A and 1B. The combined assimilation of SAR swell spectra and altimeters wave heights corrects both the wind-sea and the swell, which is independent of the wind and can propagate freely over long distances for many days. The most striking example of the impact of assimilating SAR directional swell spectra is the correction of swells generated by storms in high latitudes of the southern Pacific Ocean, which propagate to French Polynesia, the United States' west coast and western Central and South America. The assimilation of SAR swell spectra from Sentinel-1 improves the peak period of long waves longer than 12 s by roughly 16% (Aouf et al., 2018b). As swell is free of wind dependency, the assimilation of SAR swell spectra is persistent, staying effective for up to 3 days in the forecast period.

The French-Chinese satellite CFOSAT, with its innovative wave scatterometer called SWIM (Surface Waves Investigation and Monitoring), was launched in October 2018 (Hauser et al., 2017). It will measure significant wave height at nadir and retrieve directional wave spectra from combined incidence angles (ranging from 2° to 10°) every 70 km. The SWIM wave spectra will improve the wavelength azimuthal cut-off to 70 m from 200 m for SAR wave spectra retrieved from Sentinel-1. This means that more mixed-seas wave systems will be included in the assimilation process. The global CMEMS-MFC is ready to use such directional wave observations, with complementary impact between CFOSAT and Sentinel-1. OSSEs have demonstrated a significant positive impact on the integrated wave parameters (Aouf et al., 2018b).

Synthesis

The use of OSEs and OSSEs, along with regular assessment of the impact of observations on data assimilation systems, is central to the CMEMS strategy. Results depend on the data assimilation systems themselves. To derive robust results, the use of multiple systems is preferable, when feasible. Regardless, OSEs and OSSEs provide relevant information on how observations constrain ocean analyses and forecasts that feed downstream applications and users.

It is important to note that most of the OSEs/OSSEs studies described above are based on integrated global and regional ocean observing systems. They take into account the role of modeling and data assimilation (i.e., a model forecast provides better *a priori* information compared to climatology). The impact of a given observing system is not analyzed independently of the other components (e.g., the impact of Argo takes into account the synergy with satellite altimetry), providing a much better and more realistic measure of the impact of a given observing system.

SATELLITE OBSERVATIONS USED BY THE COPERNICUS MARINE SERVICE: STATUS AND REQUIREMENTS

Initial Requirements and Status

Satellite requirements for the Copernicus Marine Service have been detailed in the GMES Marine Core Service (MCS) implementation group report (Ryder, 2007; Le Traon, 2018). They are briefly summarized below:

- In addition to meteorological satellites (polar-orbiting, geostationary), a high-precision infrared SST satellite mission is needed to give the highest absolute SST accuracy. A microwave mission is also needed to provide an all-weather global observation of SST.
- At least four altimeters are required in order to observe the mesoscale currents. This is also useful for significant

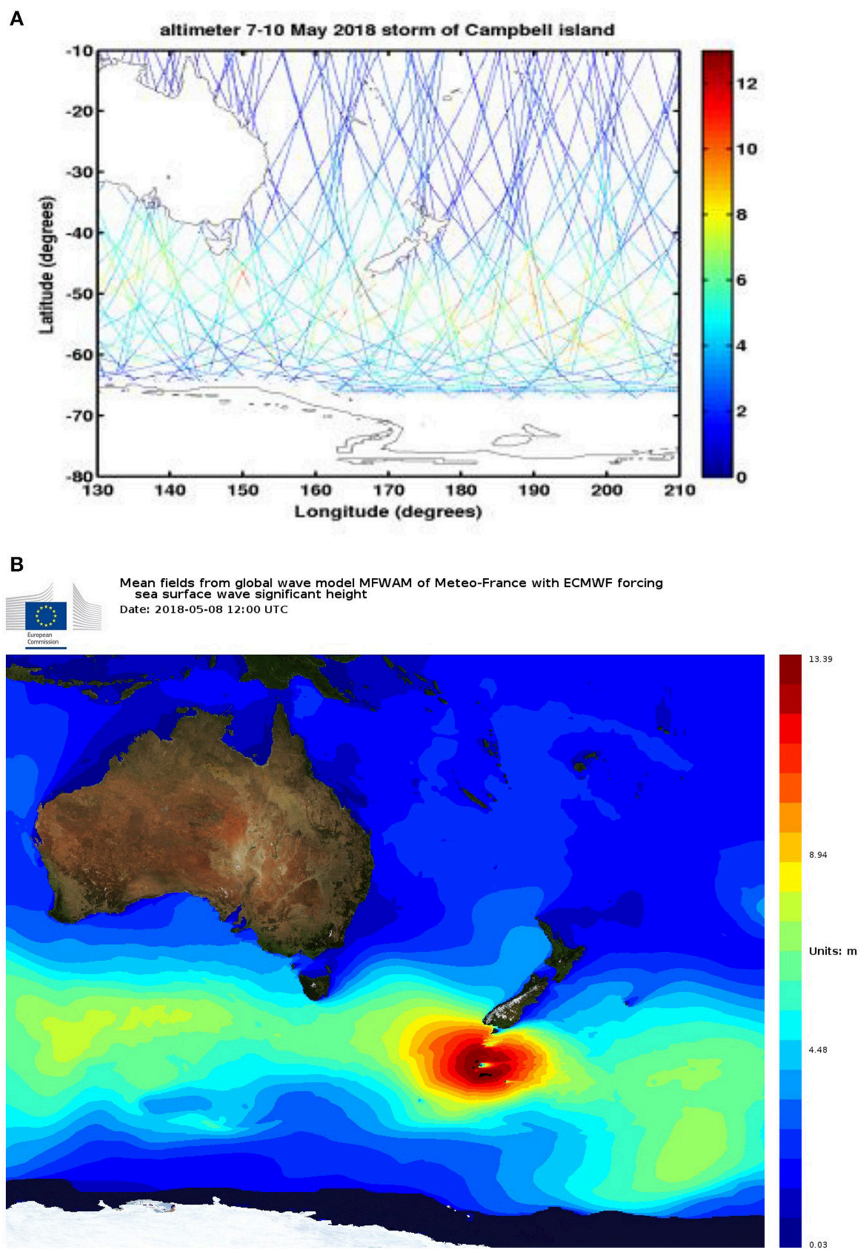

FIGURE 7 | (A) Significant wave heights on ground tracks from 5 altimeters during the storm at Campbell Island (south of New Zeland) from 7 to 10 May 2018. **(B)** Significant wave heights from the global CMEMS-MFC wave system on 8 May 2018 at 12:00 UTC. High waves induced by a severe storm, with SWH of 13.8 meters at Campbell Island south of New Zealand.

wave height measurements. A long-term series of a high-accuracy altimeter system (Jason satellites) is needed to serve as a reference for the other altimeter missions and for the monitoring of climate signals.
- Ocean color is increasingly important, in particular, in coastal areas. At least two concurrent low-Earth-orbit satellites are required for global coverage.
- Several wind scatterometers are required to globally monitor the near-surface wind field at high temporal and spatial resolution. Scatterometers, in combination with passive microwave radiometry, are also highly important for sea-ice monitoring.
- At least two SAR satellites are required for waves, sea-ice characteristics and oil-spill monitoring.

Thanks, in particular, to the development of the Copernicus satellite component, these initial requirements are now met, in particular, with Jason-3 (and later Sentinel 6) for the reference altimeter mission and the Sentinel 1 (SAR) and Sentinel 3 (sea-surface temperature, ocean color and altimetry) two-satellite constellations. Other complementary missions provide needed data, in particular, through other European or non-European satellites and instruments (e.g., MSG, METOP, DMSP/SSM/I, GCOM/AMSR-2, AltiKa, RadarSat, Suomi-NPP, NOAA-20, HY2A/B, CFOSAT).

Future Requirements

CMEMS has defined its main requirements for evolving the Copernicus satellite component (CMEMS, 2017). Based on user requirements and CMEMS's evolution over the next decade (see section Service Evolution), the main CMEMS recommendations/priorities for evolving the Copernicus Satellite Component (evolution and new generation of Sentinels) are as follows:

- Ensure continuity of the present capability of the Sentinel missions S1, S3, S6 for CMEMS and S2 for downstream coastal applications.
- Develop new capabilities for wide swath-altimetry. This is essential to constrain future CMEMS high-resolution ocean models and downstream coastal models.
- Fly a geostationary ocean color mission to strongly improve the time resolution of ocean color observations for European seas.
- Fly a European microwave mission [the Copernicus Imaging Microwave Radiometer mission (CIMR)] for high-spatial-resolution sea-surface temperature, sea-ice concentration, sea-ice drift, sea-ice thickness and sea-surface salinity.
- Ensure continuity (with improvements) of the Cryosat-2 mission (Copernicus Polar Ice and Snow Topography Mission) for sea-ice thickness monitoring and sea-level monitoring in polar regions.
- R&D actions should be developed, in parallel, to advance our capabilities to observe sea-surface salinities and ocean currents from space.

There are also a series of specific short-term requirements for altimeter measurements over the coming years. Given the potential impact of SAR altimetry, continuous effort is required to improve SAR processing for Sentinel-3 A/B (and future C/D) and refine the resolution of the associated products from 7 to 1 km. Continuity of Cryosat-2 altimeter high-latitudes observations of the ocean and sea-ice observations is required. Sea level in the leads would strongly improve the coverage of these regions and would maximize the use of Cryosat-2 data in CMEMS. It will also be important to include data from recently launched opportunity missions (e.g., CFOSAT and HY2B) to ensure the robustness of the CMEMS multi-mission altimeter system. Same holds for wave and wind measurements from these missions. Developing Near-Real-Time (NRT) processing of SWOT is essential for demonstrating its impact on operational applications. Finally, improving MDTs (based on the GRACE and GOCE satellite missions and *in situ* observations) is of utmost importance, given the impact in data assimilation systems (Le Traon et al., 2017b; Hamon et al., in press).

As far as ocean color data is concerned, with the presence of two-concurrent low Earth orbit operational satellites, the Copernicus Sentinel 3 A/B Ocean and Land Color Instrument (OLCI) sensor will have a dramatic impact on Ocean Color products and their quality. Monitoring rapidly evolving BGC phenomena (e.g., river outflows, phytoplankton and harmful algae blooms, sub-mesoscale features) and the coastal zone are a strong user requirement, implying an additional requirement for ocean color geostationary satellite, which would provide unique capabilities for such monitoring.

The exploitation of the high-resolution (< 60 m) multispectral sensor capabilities on board the Sentinel-2 A/B constellation is also of great interest to CMEMS. Sentinel-2 data, with a resolution between 10 and 60 m and a revisit time of 5 days at the equator, complements the lower-spatial-resolution (300 m) daily global coverage offered by the Sentinel-3 constellation; these data are highly relevant to developing new high-resolution coastal ocean color products, improving sea-ice detection and, potentially, deriving bathymetry near the coast.

CMEMS delivers near-real-time and reprocessed satellite-based information products of the sea-ice cover for the polar and global oceans. The products (e.g., the Tactical Navigation Ice Charts) are directly accessed by end users and ingested by the MFCs to constrain (and/or validate) their forecasts and re-analyses. Sea-ice concentrations are assimilated at Arctic and Global MFCs, both in real- and delayed-time mode. Ice thicknesses from Cryosat2 and SMOS are now assimilated at the Arctic MFC; the global MFC plans to assimilate such products in the near future. Sea-ice drift data are currently assimilated in the CMEMS Arctic system, but, so far, this has limited impact with respect to the assimilation of sea-ice concentration and thicknesses. Specific CMEMS requirements for polar and snow monitoring were outlined in CMEMS (2016). Sea-ice concentration from passive microwave radiometry is, by far, the better-controlled sea-ice quantity entering the operational systems. CMEMS (2016) stated the importance of ensuring continuity and improving the quality of sea-ice concentration products, both for climate monitoring and near-real-time applications. Concerning prospects for a Copernicus Space Component Expansion phase, CMEMS's prioritization of the polar regions agrees with the EU Polar Expert Group (Duchossois et al., 2018) in recommending retaining the Copernicus Imaging Microwave Radiometer (CIMR) mission as first priority.

IN SITU OBSERVATIONS USED BY THE COPERNICUS MARINE SERVICE: STATUS AND GAPS

Initial Requirements

The main global and regional (European seas) *in situ* observing systems required for the Copernicus Marine Service have been listed in the GMES MCS implementation plan (Ryder, 2007). They include:

- Argo floats for measuring temperature and salinity profiles to ∼2,000 m and, by tracking them, mean subsurface currents.
- Research vessels, which deliver complete suites of multidisciplinary parameters from the surface to the ocean floor.

- XBTs launched underway by research vessels and ships of opportunity for measuring temperature and salinity profiles to ~450–750 m depth.
- Moorings capable of continuously measuring, over long periods of time at fixed locations, subsurface temperature and salinity profiles, currents, waves, biogeochemical and meteorological parameters.
- Ferry-Box and other regional ship-of-opportunity measurement programmes for surface transects, which may include temperature, salinity, turbidity, chlorophyll, nutrient, oxygen, pH, CO2 fugacity and algal types.
- The network of tide gauges, which provides long-term reference and validation sea-level data.
- Gliders, which complement floats and moorings and are able to perform transects of physical and biogeochemical parameters from the surface to 1,000 m.
- Surface drifters, which passively follow the horizontal near-surface flow via a drogue/sail. They complement satellites for sea-surface temperature measurements.
- Long-range (up to 200 km) HF-radar monitoring systems in specific regions of interest and importance.
- Sea mammals, fitted with non-invasive miniaturized ocean sensors that can help collect measurements in remote places, such as polar areas.

Status—*In situ* Observations From the CMEMS *in situ* TAC

The CMEMS *in situ* Thematic Assembly Center (INS-TAC) is the main interface between CMEMS and the global, regional and coastal *in situ* observing networks. Its role is to collect, process and quality control the upstream *in situ* data required to both constrain and directly validate modeling and data assimilation systems and to directly serve downstream applications and services.

The main types of *in situ* observing systems aggregated by INS-TAC include all the platforms identified in Ryder (2007) and many others. These systems were made available over the years, when their quality was deemed appropriate to meet service requirements.

The INS-TAC provides vertical profiles and time-series data coming from different types of instruments (e.g., floats, drifters, moorings, gliders, tide gauges, vessels, HF radars) and for different parameters (temperature, salinity, currents, sea level, wave, chlorophyll, oxygen, nutrients, pH, fugacity of CO_2). The INS-TAC delivers aggregated data sets spanning near-real-time products that are delivered within 24 h, having completed automatic quality processing from acquisition, to scientifically assessed reprocessed (REP) products. The first type of product is used by the MFCs to generate and validate their forecasts, while the second type is used for reanalysis purposes.

The INS-TAC does not operate any *in situ* observing systems, rather interacting with the platform operators to collect and aggregate the best-possible version of their data. At the global scale, INS-TAC collaborates with the JCOMM networks (Argo, DBCP, OceanSites, GOSUD, OceanGliders, GO-SHIP, GLOSS), and the main international [e.g., the US National Center for Environmental Information (NCEI) World Ocean Database (WOD), the US National Data Buoy Center, the Australian Integrated Marine Observing System (IMOS) and European [SeaDataNet, International Council for the Exploration of the Sea (ICES), EMODnet] aggregators. At the European scale, the INS-TAC mainly collaborates with the EuroGOOS Regional Operational Oceanographic Systems (ROOS) and their task teams, which operate and coordinate most of the regional monitoring systems. Several EuroGOOS task teams have been established in recent years, in particular, for coordinating different observing platforms in Europe [FerryBox, Tide gauges, Gliders, HF radars, Argo floats (Euro-Argo), Fixed platforms (EMSO) and Animal-borne instruments]. One of their objectives is to link data management standards within CMEMS INS-TAC with those of existing global networks. In some cases, these task teams, such as the HF Radar EuroGOOS Task Team, have enabled the integration and enhancement of a completely new technology network.

At the global scale, the most important source of profile data for INS-TAC is the Argo network (about 4,000 platforms cycling every 10 days) and its extensions to the deep ocean and biogeochemical parameters. It is complemented by XBT lines (about 50 lines, half of which were active in 2018), sea mammals in high latitudes and, in delayed mode, the GO-SHIP hydrographic sections (60 lines in 2018) and other research cruises observations from US-NCEI and CCHDO (CLIVAR and Carbon Hydrographic Data Office). In European seas, glider data, especially in the Mediterranean and the North West shelves, as well as Conductivity, Temperature, Depth (CTD) monitoring for the Nordic and Baltic Seas can be found in the INS-TAC database. Global ocean research cruise data from SeaDataNet complement delayed mode coverage.

For time-series data, the most important source of observations is the DBCP network, which operates more than 1,400 drifters and 20 Arctic buoys. It is complemented by the GOSUD and Voluntary Observing Ships (VOS) network that provide both SST and SSS observations, as well as surface carbon data. The Argo network also provides time-series of temperature and salinity at the surface and at drifting depth, along with derived velocity information. In European seas, FerryBox lines (mainly the Baltic and North West shelves), tide gauges all along the European coasts, and coastal monitoring stations operated by EuroGOOS ROOS members also are integrated in the database. Finally, as for profile data and for reprocessed products, time-series data sets are complemented with historical research data from the US-NCEI-WOD database, from SeaDataNet NODCs, and for biogeochemical data, from EMODnet-Chemistry and ICOS (Integrated Carbon Observation System) Ocean Thematic Center.

Thanks to the Argo program, global coverage for the Essential Ocean Variables (EOVs) temperature and salinity is fine, but significant gaps appear for the abyssal ocean, seasonally ice-covered seas, fine scales and in coastal and shelf seas. Similarly, the coverage is much better for physical than for biogeochemical variables.

Figure 8 shows the *in situ* data available from the INS-TAC over a three-month period (January to March 2018). The number of *in situ* data available per EOV (temperature, salinity, current, waves, sea level, oxygen, chlorophyll, nitrate, pCO2,

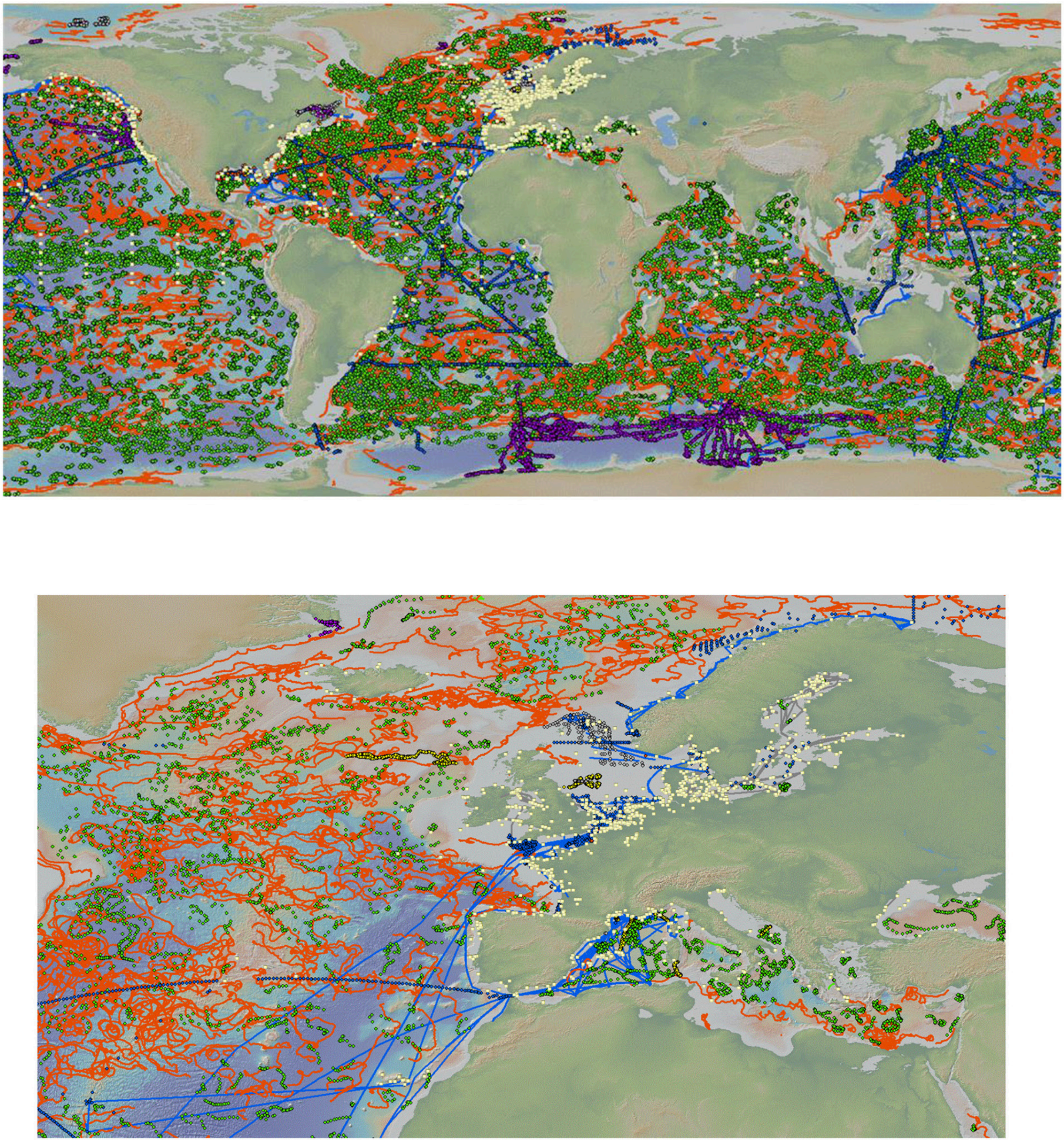

FIGURE 8 | Data at INS-TAC for Spring (January-March) 2018. Argo (green), vessels (XBT and CTD, thermosalinograps (blue), sea mammals (purple), gliders (yellow), moorings, tide gauges and rivers (white) (global and zoom on European seas).

turbidity, pH) in near-real time for a given month (June 2018) is shown in **Figure 9** for both the global ocean and European seas. Similar coverage for global and regional seas is observed, but physical parameters (temperature, salinity, currents, waves, and sea level) have better coverage in European seas. The gaps for biogeochemical EOVs at global and regional scales are clearly highlighted. Even though the coverage is improving, thanks to the development of autonomous platforms, such as BGC-Argo, FerryBoxes or gliders, it is still far less than CMEMS needs.

Use by MFCs and TACs and Future Requirements

Global

The CMEMS global ocean analysis and physical forecasting system assimilates *in situ* temperature and salinity profiles and time series from Argo floats, XBTs, CTDs, moorings, gliders and sea mammal measurements (e.g., Lellouche et al., 2013). At the global scale the assimilation of Argo observations provides an

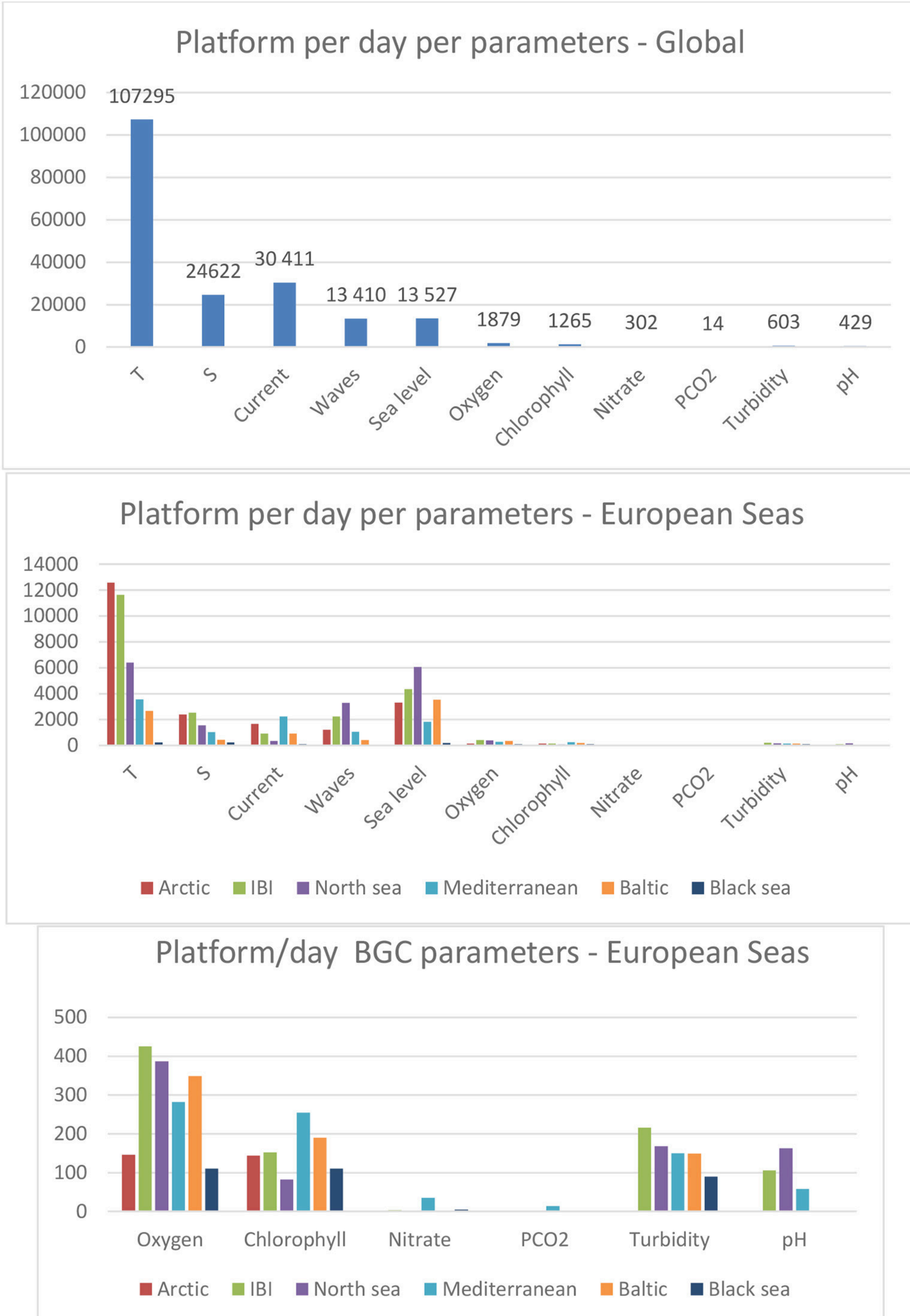

FIGURE 9 | Number of platforms providing observations per day (June 2018) by parameter (temperature, salinity, current, waves, sea level, oxygen, chlorophyll, nitrate, pCO2, turbidity, pH): **(Top)** global scale, **(Middle)** European seas (20N - 90N, 30W - 40E), and **(Bottom)** zoom on biogeochemical (BGC) data for the European seas.

efficient constraint on large-scale ocean temperature and salinity in the upper-2,000 m. Other platforms target processes having different spatial and temporal scales and constrain the analyses at regional/local scales. However, some regions remain under-sampled, such as the Southern Ocean, the Arctic Ocean or the deep ocean, which limits the ability of the system to represent the global ocean state.

Some available observations are not (yet) assimilated in the global systems [e.g., surface drifters, ThermoSalinoGraphs (TSG) and FerryBoxes]. Non-assimilated observations are, however, essential for independent qualification/validation of analyses and forecasts and for evaluating model and system improvements. In particular, model velocities are systematically validated with observations from surface drifters, Argo, HF radars and moorings, while tide gauges allow validating sea-level variability in coastal regions.

The BGC, sea-ice and wave analysis and forecasting systems are currently constrained by satellite observations only and do not yet assimilate *in situ* observations. BGC *in situ* observations are used for model development and analysis validation. BGC Argo floats increasingly provide observations of oxygen, chlorophyll, pH and nitrate. The GLODAP data base includes *in situ* data for oxygen, nutrients, dissolved inorganic carbon and alkalinity from other platforms than the Argo floats. Similarly, *in situ* sea-ice observations, more specifically the thickness of the different ice and snow categories from the unified sea-ice Climate Data Record (CDR) data base in the Arctic, are used to validate the ice model. Significant wave height and period (peak and mean) from buoys are essential for validating global wave products.

In the future, the following variables should be observed with better global coverage:

- BGC measurements: oxygen, nitrate, pH, CO2 fugacity, alkalinity, Chl-a.
- Deep temperature and salinity measurements (below 2,000 m).
- *In situ* velocity observations.
- *In situ* sea-ice observations, including thickness, temperature and snow depth.
- Open-ocean wave measurements.

The main need is to collect measurements for under-sampled variables (e.g., velocity, BGC) and under-sampled regions (e.g., polar and deep oceans). The development of the global *in situ* Argo BGC array constitutes a strong priority for CMEMS, because the lack of *in situ* BGC data limits our ability to monitor and forecast the state of the "green" ocean.

Arctic

Key variables to characterize the water masses and their variability within the Arctic are temperature, and salinity, together with ice properties (thickness, drift). Today these variables are measured by ice-tethered profilers (ITP), acoustic tomography, Argo floats, sea mammals, moorings, drifters, and, when possible, by research cruises CTD. At the moment, the number of such platforms is very limited and insufficient to monitor the entire region. In the coming decades, the Barents Sea may become ice-free all year round and would need conventional ocean monitoring technology, but other shelf seas are likely to keep a seasonal ice cover. There are severe limitations with measurements within the seasonal ice zone, which is growing broader, and none of the platforms available today can collect data there.

During the International Polar Year (IPY) (2007–2009) several Ice-Tethered Profilers (ITPs) were deployed, registering temperature and salinity profiles. These proved able to cut, by half, errors in water mass properties in the ARC MFC reanalysis (Xie et al., 2017), especially in the Atlantic water layers. Since the IPY, the number of ITPs has severely dropped, so augmenting the number of ITP, up to the level of the IPY (5 to 10 ITPs) or higher, would enable higher forecast quality in the Arctic. The perennial ice coverage available for ice-tethered equipment, however, has also further diminished in the meantime, limiting the zone where ITPs can operate for a long time. Marine mammals make a more agile sampling of the seasonal ice zone but their data need delayed-mode processing and are not assimilated in real-time forecasts. Research cruises are more frequent in the summer, but data are seldom transmitted in real-time. Acoustic tomography can also provide integrated temperature observations of high accuracy, but their use in data assimilation is still underdeveloped.

BGC data in Arctic waters, nutrients in particular, are necessary for predicting primary production, but not all observations are publicly available or harmonized for processing long time series. Autonomous platforms, like BGC-Argo should, therefore, be prioritized.

Operational wave buoys data are not publicly available, except in Iceland; although historical data exist in the offshore industry. As a rule of thumb, the safety of shipping and fishing activities will require a dozen of those, evenly spaced along the Northern Sea route. With reduced ice cover, observations of waves by accelerometers in sea-ice are also expected to become increasingly important.

With respect to sea-ice, a high priority should be given to *in situ* ice thickness, snow depth and ice temperature, as they are expected to improve satellite retrievals of ice thickness. To this end, more ice mass balance (IMB) buoys (autonomous instruments equipped with acoustic sounders and temperature/pressure sensors that are specifically designed to monitor variation of the sea-ice layer and its snow cover) are needed. With summers getting warmer, observations of melt ponds also are becoming all the more important. The first priority parameters would be melt pond area fraction and albedo, which can be used to validate satellite data and models. Other important melt pond variables will only be available on small scales and should, therefore, be used for model process parameterization (e.g., melt pond topography, multi-spectral albedo, ice thickness below melt pond).

North West European Shelf

The North West Shelf (NWS) MFC routinely downloads and quality controls satellite data, as well as *in situ* temperature and salinity profiles from Argo floats (only available in the off-shelf areas), drifters, gliders, moored buoys, marine mammals, and research ship observations for data assimilation. For verification and validation purposes, drifter-derived currents, HF Radar and tide gauges are used. There is a need to increase the *in situ* data coverage, especially on the shelf. Currently, the low spatial and temporal sampling of the sub-surface in the North, Irish and Celtic Seas, coupled with a lack of current and air-sea flux observations, hinders progress in identifying and reducing model biases. The number of BGC observations is unsatisfactory and, it should be noted, the BGC Argo observations, so useful elsewhere, will not be available on the shelf. Complementary techniques, such as increased use of gliders and FerryBoxes (to include biogeochemistry) would be welcomed. Data availability in real-time, for all types of observations, plays a key role for data assimilation, verification and monitoring; therefore, timeliness is a clear requirement for a forecasting system.

Iberian-Biscay-Ireland

The Iberian-Biscay-Ireland (IBI) MFC assimilates temperature and salinity vertical profile data from Argo floats. Product quality metrics are computed using data from multiple platforms, such as moored buoys, Argo and BGC-Argo floats, drifters, gliders, XBTs, CTDs, HF Radar. The coverage of *in situ* data in shelf/coastal areas is still too scarce. In the future, it will be important to increase the number of near-real-time *in situ* observations in shelf and in coastal areas of the IBI region. HF Radars are useful for monitoring high-frequency surface circulation dynamics. To better monitor the three-dimensional circulation on the shelf, more acoustic Doppler current profiler (ADCP) observations (if possible, available in NRT) are needed. *In situ* BGC data coverage in the IBI area certainly must be enhanced. The current lack of these *in situ* data is a major shortcoming that prevents the estimation of meaningful biogeochemical monitoring indicators in the area.

Mediterranean Sea

There is a recognized concern about the status of the Mediterranean observing system and its future. There are important gaps due to the lack of instruments and poor data policy, in particular for central-eastern Mediterranean Sea and the northern African coast, leading to a strong North-South West/East imbalance.

When looking more specifically at platform types, at MED-MFC Argo floats, CTD and XBT platforms are assimilated into the system and also used for quality assessment, while moorings are used only to assess the quality of the system through independent validation. The existing coverage of the Argo network is about 60 active floats in the Mediterranean Sea, which is twice the standard Argo density. This should be, at least, maintained as recommended by the Euro-Argo ERIC (European Research Infrastructure Consortium) (Bittig et al., 2017). Full-profile vertical resolution is required for CMEMS operational analyses. There is also a need for an increased number of Argo floats in highly dynamical areas and for the deep region. This goes along with the need to reintroduce XBT measurements and to increase the number of *in situ* velocity observations (e.g. ADCP, moorings, HF Radars, drifters).

Wave buoy observations of significant wave height and mean wave period are used to calibrate and validate the Med-waves modeling system. Maintaining and increasing the number of wave buoys and including wave measurements from HF Radars are required, in particular in the central and eastern Mediterranean and along the African coasts.

A clear need exists for increased coverage in the eastern and southern Mediterranean in terms of the number of BGC-Argo floats and number of moorings equipped with BGC sensors.

Black Sea

The Black Sea MFC (BS-MFC) physical modeling system assimilates temperature and salinity profiles from Argo floats, moorings, XBT, and bathythermographs (MBT). There is a clear lack of data to be regularly used for improving forecasts products. In particular, to better represent coastal dynamics, regularly updated and continuous-in-time coastal profilers and moorings are requested. The *in situ* observing system should evolve, accounting for the importance of having coastal observatories, in particular wave buoys, ADCP and HF radars to feed the next generation of BS physical and wave modeling. *Ad hoc* and continuous monitoring is required in the shelf area, especially in the northern part of the Black Sea and in the Danube Delta. The Black Sea wave model suffers from a lack of *in situ* wave measurements.

For near-real-time validation, the BS-MFC biogeochemical model (Grégoire et al., 2008) essentially relies on BGC Argo floats that provide oxygen, fluorescence, the photosynthetically active radiation and backscattering coefficients. The system, however, suffers from the lack of regional data to regularly be used for improving the validation exercise and for assimilation. In particular, as an anoxic basin, the dynamic of the carbonate system (pH, dissolved inorganic carbon and alkalinity) and the conversion of *in situ* fluorescence into chlorophyll (e.g., from BGC-Argo floats) require particular algorithms supported by adequate monitoring efforts. The lack of carbon system observations currently prevents a sound assessment of acidification in the Black Sea and its modeling. Moreover, being a turbid area, with anomalously high colored dissolved organic matter, Black Sea shelf waters require extensive observations for assessing its inherent optical properties in support of developing high-quality ocean color products. So far, the biogeochemical variable that has the best spatial and temporal coverage is oxygen, because it is provided by BGC Argo floats (Stanev et al., 2013, 2018). On the shelf, where there is evidence of seasonal hypoxia, the monitoring of oxygen is crucial. BGC Argo floats cannot go there. Cruises, moorings and gliders offer alternative solutions.

Baltic Sea

For the Baltic Sea, CMEMS's *in situ* ocean observations include FerryBox lines, moorings, Research Vessels (R/Vs), tide gauges and Argo floats. In recent years, HF radars have been tested in the transition waters and gliders have been tested in the central Baltic Sea. Although the deployed platforms are providing data with sufficient spatial and temporal resolution, coverage should be improved: the Baltic Sea includes 17 sub-basins, with significant spatial variability in physical and biogeochemical characteristics, thus requiring *in situ* observations in all sub-basins to ensure spatial representativeness in the validation of regional products.

In general, more moorings for temperature and salinity are needed in the Danish straits and more stations for BGC measurements should be deployed over the central and northern Baltic areas (more than half of the sub-basins have insufficient data for assessing eutrophication). An optimal sampling design is needed for integrating the multi-platforms, especially through enhancing the role of shallow-water Argo floats. Finally, data management also should be improved. The Baltic Operational

Oceanographic System (BOOS) partners are also members of the HELCOM monitoring program for environment assessment, which is carried out mainly through ship monitoring. The observations, having low sampling frequency and full spatial coverage, include most of the EOVs and Essential Biodiversity Variables (EBVs); however, most of the ship data cannot be accessed in a timely manner for operational forecasting and ocean state assessment reporting. Currently, only 10% of BOOS partners provide near-real-time ship data.

Specific Requirements for the Validation of Satellite Data Products

The calibration and validation of the upstream (Level-2) satellite data are the responsibility of ESA and EUMETSAT, which are working to develop a dedicated *in situ* observation system to ensure the acquisition of high-quality *in situ* measurements, accompanied with their uncertainties, also referenced to as "Fiducial Reference Measurements" (FRM). These measurements can be used by CMEMS TACs and MFCs for their validation activities. It is important that CMEMS requirements are taken into account when designing and developing new platforms for acquiring FRM.

Satellite-based sea-level (and geostrophic velocity) measurements are validated using tide gauge networks, drifting buoys, gliders, HF radar, ADCP and Argo profilers. While, at the global scale, the number of available *in situ* observations is adequate to routinely conduct validation, at the regional level, particularly for the Mediterranean Sea and Black Sea, available tide gauge datasets are still too limited for a robust validation.

In situ data are used to evaluate and calibrate ocean color remote sensing algorithms and to validate the operational products distributed by CMEMS. These measurements are acquired through a variety of systems and platforms, such as automated in-water and tower-based radiometers, and from profiles acquired during dedicated research cruises. At the moment, these observations are very sparse and limited. There is a clear need for improving the number of platforms able to perform such measurements. Additionally, the future systems should be designed to allow a NRT data stream and enable operational capabilities that meet CMEMS service needs. Given the potentially large number of match ups with satellite observations, the use of BGC Argo data offers a complementary approach for the routine validation of satellite ocean color products.

Validation of SST products is operationally done using *in situ* data acquired from surface drifting buoys, Argo floats, *in situ* ship radiometers and moored buoys, as independent source of comparison. *In situ* data need to be collected at the highest available frequency and they should contain more metadata to better select and/or filter out data for confidence in the validation. Satellite sensors provide measurements of the skin layer; however almost all CMEMS interpolated products are built to represent the "foundation" temperature (namely the temperature at a depth that is not affected by skin effects and by the diurnal cycle). Nevertheless, significant differences can be found between *in situ* observations collected at different depths, depending on the local time and atmospheric conditions. In terms of coverage, it is recommended that measurements over the Black Sea, the Baltic Sea and the Arctic region be increased due to the very low number of observations there. An additional important requirement for satellite validation is to have the *in situ* measurements available in near-real-time, e.g., within 24 h of acquisition.

Validation of sea-ice products derived from satellite measurements is carried out using ship measurements from ice breakers, ice mass balance buoy measurements, drifter Global Positioning System (GPS) buoys, and ITP. At the moment, there is a great lack of *in situ* data for both the Arctic and Antarctic regions.

For wind and wave measurement validation, it is recommended that the number of moored buoys, the main platform used for validation, be increased to better represent regional geophysical conditions. Most wave buoys are located in the northern hemisphere near U.S. east and west coasts and European coasts. There is a clear need to cover tropical and the southern ocean basins to validate new satellite wave data, such those provided by CFOSAT and Sentinel-1. It would be very useful, in particular, to include wave sensors in the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) and Tropical Pacific Observing System (TPOS) tropical networks. Such sensors will help, on the one hand, validate the assimilation of SAR wave spectra in CMEMS wave models and, on the other hand, to better describe heat and momentum fluxes for the ocean-atmosphere coupled system.

It is important to note that, to better link Argo observations with satellite observations, bearing in mind sensor technology limitation issues, efforts should be carried out to better sample the top 5 meters of the ocean.

CONCLUSION

The Copernicus Marine Service has run a successful initial phase over the past 4 years. Operational capabilities have been demonstrated, user uptake and user base have been steadily increasing and service evolution activities allow regular improvements of the products and services provided to users. Observations are a fundamental pillar of the CMEMS value-added chain, thus CMEMS is highly dependent on the timely availability of comprehensive satellite and *in situ* observations. This core dependency is managed by CMEMS to ensure its requirements are incorporated in observation plans. The main role of CMEMS is to detail its requirements (from an integrated system perspective), carry out impact assessments and interact with the Copernicus satellite and *in situ* components for implementation issues. The role of CMEMS is also to advocate on the fundamental role of observations for the services it provides.

Based on an analysis of existing and future observing capabilities, impact assessment studies and long-term service evolution plans, the main CMEMS recommendations for the evolution of the ocean observing system can be summarized as follows:

- Continuity of the present capabilities of the Sentinel missions should first be ensured. In addition to already decided missions, such as SWOT, that are expected to have an important impact on CMEMS (Morrow et al., 2019), new capabilities should be developed on the medium (before 2025) and long term (after 2030). In the medium term, a European passive microwave mission for high-spatial-resolution ocean surface temperature, sea-ice concentration, sea-ice drift, thin sea-ice thickness and sea-surface salinity should be developed. Continuity (with improvements) of the Cryosat-2 mission for sea-ice thickness and sea-level monitoring in polar regions should be ensured. It is also important to fly the SKIM (Sea surface KInematics Multiscale monitoring) surface current R&D mission to demonstrate its potential for CMEMS. In the longer term, new capabilities for operational wide-swath altimetry and geostationary ocean color mission over Europe should be developed.

- As far as the *in situ* observing system is concerned, there are critical sustainability gaps, sampling gaps and major BGC observations gaps (e.g., carbon, oxygen, nutrients, chl-a). In terms of EOVs, these gaps should be filled through different networks. The evolution of satellite observations toward higher space/time resolution also suggests that maintaining and enhancing the *in situ* observing system are critical for validating and complementing future high-resolution satellite observations. In terms of platforms, consolidation of the Argo core mission (temperature and salinity—0 to 2,000 m), including the sampling of polar and marginal seas and developing its two major extensions (BGC Argo and Deep Argo) (Roemmich et al., in review), is a strong priority for CMEMS at global and regional levels. Nowadays, Argo is the key *in situ* network for operational oceanography, providing thousands of daily measurements of ocean physics and, progressively, becoming the main source of BGC observations in the open seas. Argo needs to be complemented by reference measurements from long time series at fixed points from moorings and ship-based hydrographic surveys with the best quality (GO-SHIP) standards. Improving ROOSes and key observing systems, such as FerryBoxes, gliders, tide gauges and HF radars, are strong priorities for regional CMEMS products. A specific effort for the Arctic region is needed because there are severe limitations with measurements within the seasonal ice zone, which is growing broader, and none of the platforms available today can collect data there. Developing a dedicated network capable of collecting FRMs for all the ocean variables estimated by the Copernicus Satellite component is also important for CMEMS.

These requirements will evolve over time as CMEMS's integrated systems develop. It is essential to strengthen CMEMS capabilities for assessing the impact of present and future observations (particularly for BGC EOVs) to guide observing system agencies, as well as to better use observations in models. These activities should be developed further in Copernicus 2.0 (post 2021) in cooperation with international partners.

The development of improved and more integrated *in situ* and satellite observing systems required by CMEMS will also require strengthening international cooperation and coordination on observations (GOOS, CEOS), modeling and data assimilation (GODAE OceanView/Ocean Predict) and applications and users (GEO Blue Planet).

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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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REVIEW
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Global Observing Needs in the Deep Ocean

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The deep ocean below 200 m water depth is the least observed, but largest habitat on our planet by volume and area. Over 150 years of exploration has revealed that this dynamic system provides critical climate regulation, houses a wealth of energy, mineral, and biological resources, and represents a vast repository of biological diversity. A long history of deep-ocean exploration and observation led to the initial concept for the Deep-Ocean Observing Strategy (DOOS), under the auspices of the Global Ocean Observing System (GOOS). Here we discuss the scientific need for globally integrated deep-ocean observing, its status, and the key scientific questions and societal mandates driving observing requirements over the next decade. We consider the Essential Ocean Variables (EOVs) needed to address deep-ocean challenges within the physical, biogeochemical, and biological/ecosystem sciences according to the Framework for Ocean Observing (FOO), and map these onto scientific questions. Opportunities for new and expanded synergies among deep-ocean stakeholders are discussed, including academic-industry partnerships with the oil and gas, mining, cable and fishing industries, the ocean exploration and mapping community, and biodiversity conservation initiatives. Future deep-ocean observing will benefit from the greater integration across traditional disciplines and sectors, achieved through demonstration projects and facilitated reuse and repurposing of existing deep-sea data efforts. We highlight examples of existing and emerging deep-sea methods and technologies, noting key challenges associated with data volume, preservation, standardization, and accessibility. Emerging technologies relevant to deep-ocean sustainability and the blue economy include novel genomics approaches, imaging technologies, and ultra-deep hydrographic measurements. Capacity building will be necessary to integrate capabilities into programs and projects at a global scale. Progress can be facilitated by Open Science and Findable, Accessible, Interoperable, Reusable (FAIR) data principles and converge on agreed to data standards, practices, vocabularies, and registries. We envision expansion of the deep-ocean observing community to embrace the participation of academia, industry, NGOs, national governments, international governmental organizations, and the public at large in order to unlock critical knowledge contained in the deep ocean over coming decades, and to realize the mutual benefits of thoughtful deep-ocean observing for all elements of a sustainable ocean.

Keywords: deep sea, ocean observation, blue economy, essential ocean variables, biodiversity, ocean sensors

THE MANDATE AND BASIS FOR SUSTAINED DEEP-OCEAN OBSERVING

Scientific Need for Globally Integrated Deep-Ocean Observing

Climate change, pollution, man-made structures and extraction of living and non-living resources will impact the deepest reaches of the global ocean (Mengerink et al., 2014). Despite these increasing threats, our understanding of the affected ecosystems and the nature of these impacts remains very limited. The vast majority of our oceans remain unseen and unquantified (Copley, 2014) in the face of current and emerging industrial activities and in spite of technologies that have expanded our capability to carry out globally integrated deep-sea observation.

Here we consider the deep sea to encompass waters below 200 m. Physical oceanographers in the past defined the deep ocean as approximately 1,000 m based on an assumption of levels of no motion, but now we know these waters are dynamic. There was early recognition of 200 m as a useful approximate planetary-scale boundary between neritic and oceanic conditions and between the epipelagic and deep-ocean realms (Hedgpeth, 1957). Below 200 m, changes in light, food supply, and the physical environment lead to altered animal taxonomic composition, morphologies, and lifestyles that are collectively understood to represent the deep sea both within the water column (Herring, 2002) and at the seafloor (Gage and Tyler, 1991; Tyler), 2003; Ramirez-Llodra et al., 2011; Levin and Sibuet, 2012; European Marine Board, 2013; Danovaro et al., 2014, 2017). Additionally, strong changes in biological and biogeochemical processes from 200 to 1000 m have a large influence on greater depths.

The deep sea is a highly connected environment, with links to the atmosphere and upper ocean as well as across depths and ocean basins. Contaminants, pollutants, and human exploitation readily cross oceans and political boundaries, as do the species, ecosystems, and biogeochemical processes that they impact. At the same time, many small-scale deep ocean phenomena, such as chemosynthesis-based hydrothermal vent, methane seep and organic (whale and wood) fall communities (e.g., Nishi and Rouse, 2014) contribute greatly to the Earth's biodiversity.

The great expanse of the deep ocean has to this point resulted in an extremely poor spatial and temporal resolution of observation. If future changes, threats, and impacts are to be appropriately monitored to enable mechanistic understanding and move toward sustainable management, that situation must change. A globally integrated deep-ocean observing system will require substantial international cooperation, collaboration and agreement, the support of many agencies and industries, and the adoption of 21st century remote and autonomous technologies.

Status of Deep-Ocean Observing

Recognition of observation as key to the health of the oceans and sustainability of human activities on the planet has accelerated observing efforts since 2000, particularly in the upper ocean (Visbeck, 2018). However, the deep ocean remains under sampled and under observed at great depths and in many regions. For example, only 2% of observations in the Ocean Biogeographic Information System (OBIS) are from water depths greater than 500 m (Vanden Berghe, personal communication), despite recognition of high biodiversity in the deep ocean over the past half century (Rex and Etter, 2010). Multiple sustained observing programs and observatories in the coastal ocean (Corredor, 2018), global ocean (e.g., ARGO, OceanSITES, GO-SHIP, OOI, ONC, EMSO), and on basin and regional scales (e.g., TPOS 2020, AtlantOS, SOOS, FRAM), carry out deep-ocean observations at near continuous to 10-year intervals. But the ocean is vast, and, even with these observations, measurements are sparse. This is particularly true in the southern hemisphere, at depths below 2000 m (the maximum depth of most Argo floats), and for biological variables. For example, the Volunteer Observing Ship (VOS) program that deploys XBTs (expendable bathythermographs) along commercial ship tracks, providing valuable repeat sections, uses T7 XBTs which go only to 760 m and only measure temperature. In response, the Deep Ocean Observing Strategy (DOOS) represents a growing effort by the scientific community, under the auspices of the Global Ocean Observing System (GOOS), to coordinate and expand deep observing efforts, particularly with respect to essential ocean variables (EOVs) (**Box 1**).

As part of the DOOS effort, a 2016 census of sustained observations in the deep sea was conducted (**Figure 1**); it received 72 responses from 52 organizations, representing 75 countries, for programs funded by 55 agencies. Most program-wide sampling occurred across large depth ranges (200–6000 m) and spatial scales. The most common mature EOVs sampled were temperature, salinity, dissolved oxygen, carbonate system components, and primary productivity. Research vessels, bottle samplers, and moorings were the most common platforms; the most common instruments were Conductivity, Temperature and Depths (CTDs), oxygen sensors, and acoustic Doppler profiler. These traditional observing tools are now being supplemented by a new generation of observing platforms and sensors, designed for longer duration, greater range, and the assessment of a broader suite of physical, chemical, and biological parameters. These new tools record sound and light, sequence genes, detect chemical constituents, collect high- resolution acoustic and optical imagery at any scale from marine snow particles to vast areas of seafloor habitats, provide animal-eye views, and bring exploration of the deep sea to the public.

Quantitative Understanding of Natural Variability in the Deep Ocean and Causes of Long-Term Changes

Climate change and related phenomena

As the major anthropogenic carbon and heat sink, the ocean plays a critical role in mitigating climate change and determining how these changes impact society. With more than 90% of the anthropogenic heat imbalance absorbed by the ocean (Levitus et al., 2012), accurately monitoring its full depth provides a fundamental constraint on quantifying the warming of the planet (Johnson et al., 2016). Climate change has direct and indirect impacts on ocean biodiversity (Booth et al., 2018b) and processes, including surface ocean effects such as acidification impacts on plankton and oxygen production (Booth et al., 2018a). Deep-ocean biodiversity loss and climate-induced regime shifts are already occurring in some areas and are anticipated elsewhere (Levin and Le Bris, 2015). Polar regions are particularly vulnerable to warming which will affect stratification and ice cover, water chemistry, food supply, sedimentation, physical disturbance, metabolic processes and ultimately the biological composition of communities in the deep ocean (Sweetman et al., 2017). Large parts of the deeper portions of the Arctic have almost never been measured, and thus we lack even a baseline of deep Arctic Ocean properties (Nguyen et al., 2017). Expanded ocean measurements are also needed in the Southern Ocean to quantify heat budgets and understand interaction with shelf waters and their effects on regional climate, ice dynamics and ecology (Schofield et al., 2010). The need to anticipate extreme climate events and disruptive climate anomalies, such as El Niño, that affect ocean ecosystems and livelihoods requires

BOX 1 | Deep-ocean observing strategy (DOOS) history and status.

The deep-sea community began discussions about coordinating deep-ocean observing and the development of essential ocean variables (EOVs) in 2011 that led to the formation of the Deep-Ocean Observing Strategy (DOOS), a project within the Global Ocean Observing System (GOOS). By advocating for observing EOVs, DOOS strives to improve understanding of the state of the deep ocean with respect to baseline conditions and response to climate variability and human disturbance.

- 2011: From Space to the Deep Seafloor Workshop Conducted
- 2014: DOOS adopted as a GOOS Project (GOOS SC-3)
- 2013-2016: DOOS Consultative Draft Distributed and Posted for Review
  - Precursor to Implementation Guide: Levin, Boetius, Fischer, Johnson, Sloyan, Sibuet, Tanhua, Wanninkhof, (+ Ruhl, Heimbach, Song)
  - www.deepoceanobserving.org/reports/consultative-report/
- 2016: Deep-Ocean Observing Inventory Launched (70+ Responses)
  - www.deepoceanobserving.org/observations/deep-ocean-observations/
- 2016: DOOS Scoping Workshop Conducted (51 attendees from 9 countries)
  - Summary Report: www.deepoceanobserving.org/reports/dec-2016-workshop-report/
  - Terms of Reference: www.deepoceanobserving.org/about/doos-terms-of-reference/
  - Key Science Questions: www.deepoceanobserving.org/observations/key-science-questions/
- 2017: First DOOS Steering Committee Meeting Convened
  - Project Structure: www.deepoceanobserving.org/about/
- 2017: Project Plan and Engagement Plan Completed
- 2018: Community Communications Conducted
  - OSM Town Hall: www.deepoceanobserving.org/2018/01/18/ocean-sciences-meeting-2018-doos-town-hall/
  - Ocean Obs '19 Community White Paper submitted to Frontiers in Marine Sciences

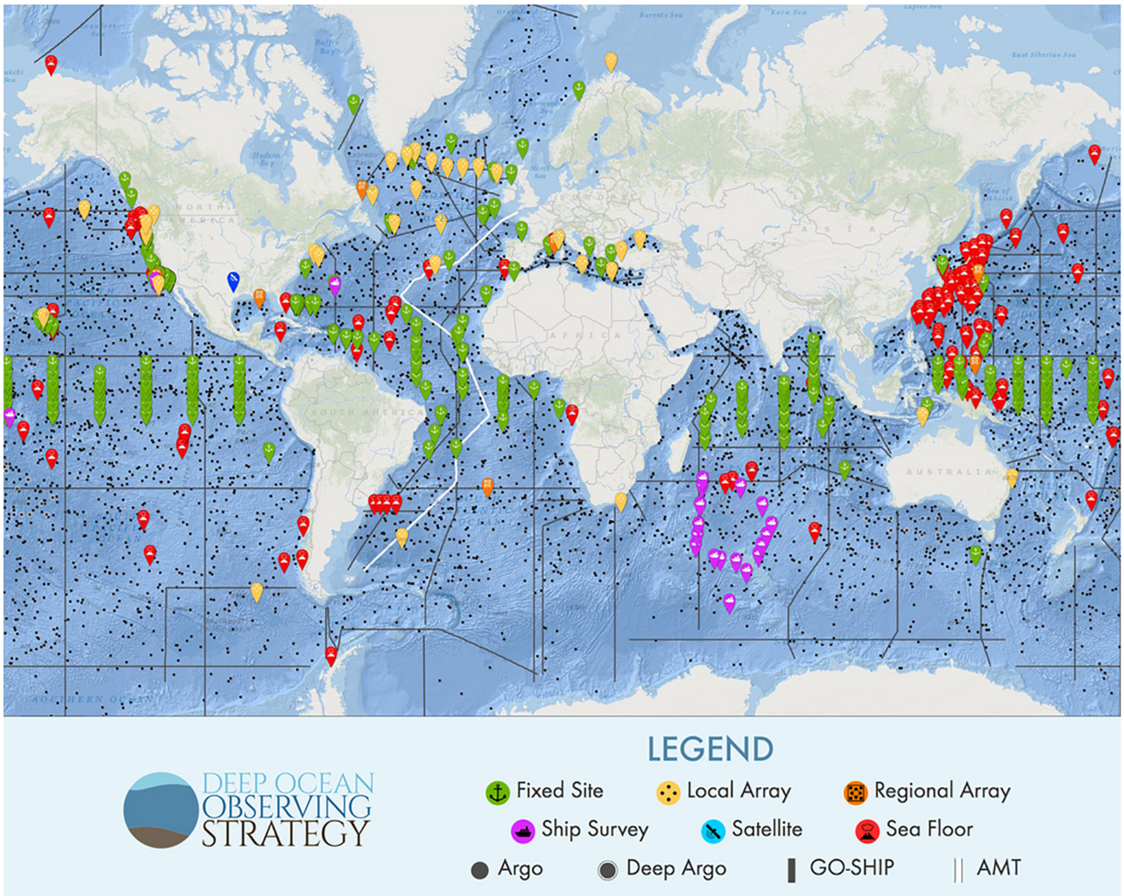

FIGURE 1 | Inventory of sustained deep-ocean observing (Interactive map available online, http://www.deepoceanobserving.org/observations/deep-ocean-observations/).

increased research into the deep ocean and its connection to the surface and atmosphere. Our ability to project future change and develop adaptive strategies to better enable society to cope with climate change would be greatly enhanced by new, well-coordinated physical, biogeochemical, and biological observations in deep waters.

The deep sea as an analog for the origin of life and its extraterrestrial potential

Extreme conditions found in deep-sea waters, at the seafloor, and in the deep biosphere offer insight into the processes enabling the origin of life and the potential for life on other planets and their moons. There are combinations of temperature, pressure, Eh, and pH found in the deep ocean that are conducive to abiotic processes that may generate primordial life (Cavanaugh et al., 2006; Schulte et al., 2006). Deep-sea settings with carbonate minerals, methane, and carbon dioxide may resemble those on Mars. Anoxic, hypersaline basins of the Mediterranean Sea support diverse microbial processes (sulfate reduction, methanogenesis, and heterotrophic activity) (van der Wielen et al., 2005) and even metazoan life forms (Danovaro et al., 2010), suggesting potential for such conditions to support extraterrestrial life, for example in water stored as brine lenses on Mars (Gilichinsky, 2002). Hydrothermal vents offer confirmation that life can thrive in the dark depths of the ocean, utilizing chemosynthesis as the base of the food chain; analogous geologically active seafloors may occur in the oceans of the moons of Jupiter (Europa) and Saturn (Enceladus), based on ejected plumes with mixtures of compounds characteristic of hydrothermal venting (Deamer and Damer, 2017). Increasingly, exploration and observation of the extreme deep sea offers unending novelty that reveals new possible modes of life on Earth and potentially other planets.

Natural resource use

The monetary value derived from the oceans, including energy, minerals, and fisheries, is estimated at USD 24 trillion (Hoegh-Guldberg, 2015). Significant assets lie in the deep ocean where the current state of knowledge is unlikely to be sufficient to guarantee safe and sustainable exploitation (Ramirez-Llodra et al., 2011). Threat prevention and mitigation require thorough understanding of the current state of the deep ocean and its natural variability (baseline data), as well as records of changing environmental quality to enable sustainable economic growth, food security and ecosystem-based management. Known natural temporal variability in deep-ocean biological assemblages (e.g., Smith et al., 2009) suggests that there is a "moving baseline" that cannot be captured by one-off observations, such that routine observations over time will be essential to appropriate environmental monitoring.

Pollution, contamination and litter

The deep ocean is the ultimate sink for materials on land; through the action of weathering and gravity, great mountain ranges are leveled and become a thin layer of sediment on the deep-sea floor. Consequently, it is no surprise that human debris, environmental contaminants, and pollutants are widespread throughout the global deep ocean. Clinker, burnt coal from the age of steam, litters most of the deep-ocean floor; today, plastic debris appears equally pervasive (Ramirez-Llodra et al., 2013). As in coastal and shelf seas, the greatest concern is likely to be persistent compounds that bioaccumulate and biomagnify (e.g., organohalogens and organometals; Kress et al., 1998; Roberts, 2002; Ramirez-Llodra et al., 2011). Such contaminants can be found in animals inhabiting the deepest trenches (Jamieson et al., 2017). These pollutants and contaminants are rarely measured. That lack of attention may stem from an erroneous perception that such compounds are not present and technical difficulties in achieving such measurements. Somewhat perversely, the contamination of the global ocean by these compounds has proved useful in oceanographic science, for example in the use of organohalogens (chlorofluorocarbons and sulfur hexafluoride) as tracers of water masses and their movement (Fine, 2011). These forms of widespread contamination of the environment and fauna of the deep ocean are little reported, in marked contrast to major point-source contaminations of the ocean such as the 2010 Macondo oil spill in the Gulf of Mexico. The full acute and chronic impacts of the Macondo accident remain a largely unanswered question. Although there is evidence of toxicity from constituents of the oil to deep-water corals (White et al., 2012) and soft-bottom benthic communities (Montagna et al., 2013), a lack of pre-spill data has limited the full assessment of impact.

Accumulations of marine debris, particularly plastic material, occur commonly in the deep sea, along with microplastics in a wide range of ecosystem compartments (e.g., Bergmann et al., 2017). Large objects such as shipping containers and fishing gear (derelict nets and trawls) can alter habitats by providing hard substrate, toxicological impacts associated with coatings or contents (Taylor et al., 2014), or entangling organisms (Humborstad et al., 2003). Plastics resist degradation and can potentially last for centuries. Documentation of macroscopic plastic debris throughout the deep sea (Ramirez-Llodra et al., 2013; Schlining et al., 2013; Chiba et al., 2018), includes observations from the Mariana Trench (Chiba et al., 2018) and the Arctic Ocean (Bergmann et al., 2017). Ingestion of macroscopic plastics by fishes is documented (e.g., Anastasopoulou et al., 2013); however, the potential impacts of microplastics (particles less than 5 mm in diameter) raises issues that are still not well understood. Microplastics have been found to be abundant in sediment samples collected from a wide range of geographic locations at depths ranging from 300 to 3500 m (Van Cauwenberghe et al., 2013; Woodall et al., 2018). Additionally microplastics have been found to enter deep-sea food webs, with ingestion of microplastic fibers documented in cnidarians, echinoderms, and arthropods collected from 334 to 1783 m in the equatorial mid-Atlantic and SW Indian Oceans (Taylor et al., 2016). Benthic invertebrates ingested microplastics at depths deeper than 2200 m in the North Atlantic (Courtene-Jones et al., 2017). Physical, biogeochemical, and biological observations can improve understanding of the sources, pathways, fates and consequences of plastic and debris in the ocean and inform mitigation practices.

BOX 2 | Key scientific questions.

1. What is the role of the deep ocean in the Earth's energy imbalance and land/sea water redistribution?
2. How are natural and anthropogenic variations in climate connected to the global overturning circulation and its variability?
3. How does deep pelagic ecology respond to natural variation and multiple climate change stressors?
4. How might natural and anthropogenic variations in climate influence the function of the solubility and biological carbon pumps, continental slope, nepheloid layer transport and the sequestering of carbon in the deep ocean, and the supply of organic carbon (food supplies) to deep-sea communities?
5. What drives observed variation in seafloor fluxes of heat, nutrients, tracers, oxygen and carbon?
6. How might natural and anthropogenic variations in climate and resource industry activities influence the functional importance of animals and microbes in the deep sea and the seafloor?
7. What are the sources, pathways, fates and consequences of deep-ocean contaminants (including plastics) introduced by humans from land and ocean activities?

Key Scientific Questions Driving Observing Requirements

Even our limited knowledge raises fundamental questions requiring answers for prediction and management of deep-ocean connected systems and processes. Below we introduce a subset of these questions that underpin observational requirements for the deep ocean (**Box 2**), largely derived from the DOOS Science Implementation Guide.

Societal Mandates

Quantifying Change Through Science-Based Management and Planning

Effective environmental management requires environmental monitoring (National Research Council, 1990). Environmental management targets different scales, from spatial planning and ecosystem-based management (Crowder and Norse, 2008) to management of individual offshore industrial projects (Ellis et al., 2017). Minimizing environmental degradation drives such management, and industry must strive to meet this goal to obtain its license to operate. Development in the marine environment in most jurisdictions requires an environmental impact assessment (EIA) process to anticipate, assess, and reduce environmental and social risks of a project prior to granting regulatory approval (Durden et al., 2018). The EIA process requires the proponent to describe the environment, estimate impacts of the project, and provide an environmental management plan (EMP), all of which demand environmental observations and establishment of a baseline of the physical, chemical and biological environment in and around the development (Ellis et al., 2017), and thus a wide range of ocean data. Most marine developments lack sufficient information for assessment at the project planning phase and thus require new data. The environmental baseline provides a reference point to assess impacts of the project relative to unimpacted "control" sites nearby (Underwood, 1992). Any project moving forward must monitor to evaluate potential impacts and their consequences to ensure appropriate management actions where significant impacts occur. Effective management typically requires good quality, quantitative environmental information. All aspects of the environmental management of deep-water industrial projects and policy bring significant uncertainty during development, punctuating the need for observational data to establish environmental conditions and responses to disturbance. Ocean observations can provide the necessary information for effective management of the marine environment, including measuring environmental baseline conditions, establishing change caused by both natural and anthropogenic activities, and in assessing recovery after disturbance. Deep-ocean observations provide the basis for prediction and modeling, where data enable model development, parameterization and testing. Deep-ocean observing also provides important information for engineering, particularly physical environmental conditions (e.g., current speeds, temperatures) and infrastructure risk (e.g., from submarine landslides, subsidence).

Socio-Ecological and Environmental Policy Making

The interactions and cumulative impacts of different human uses of the deep ocean require mechanistic understanding and comprehensive monitoring to inform integrative and adaptive management measures that ensure the long-term sustainability of critical ocean ecosystems and sustainable development. Numerous international policy-making bodies, initiatives and agreements either require or would benefit from deep-ocean observations and input from deep-sea scientists (see **Table 1**). Strong deep-ocean representation for defining critical issues, data generation, the detection of cumulative impacts, and technology transfer going forward will benefit all of these entities.

Cultural Services

The non-material human benefits obtained from the deep ocean are referred to as "cultural services." These include aesthetic inspiration, cultural identity, sense of home, and spiritual experience related to the natural environment. Education and science are sometimes included. The remote and, to humans, extremely hostile environment of the deep ocean render the prospects of tourism and recreation a rather distant prospect. Some small-scale, subsistence fishing does take place in deep-water and open-ocean environments and would be characterized as "fishers' way of life"/cultural identity. In the terminology of The Economics of Ecosystems and Biodiversity (TEEB) "Aesthetic appreciation and inspiration for culture, art and design" and "Spiritual experience and sense of place" are likely to be the primary cultural services provided by the deep ocean; in some cases these are largely provided by the media (e.g., BBC Blue Planet I and II). These concepts can be generally considered analogous with the "Common Heritage of Mankind," as incorporated in the United Nations (UN) Convention on the Law of the Sea, and considered by the International Seabed Authority in the context of proposed deep-ocean mining regulations (Bourrel et al., 2016).

GENERATING DEEP-OCEAN DATA

Essential Deep-Ocean Variables

The FOO (Lindstrom et al., 2012; Muller-Karger et al., 2014, 2018; Miloslavich et al., 2018) was developed following OceanObs'09 in Venice. It forms the basis for the identification and specification of EOVs within GOOS, and more recently DOOS. "Fit for purpose" essential variables are selected based on their ability to address pressing scientific questions and societal challenges, and on their feasibility. Proven, scientifically understood methods of sufficient readiness have to be available to allow for operational observations on a global scale. A multidisciplinary writing team of experts in the field of ocean climate, physics, carbon cycling, biogeochemistry, and biology, biodiversity and ecosystems initially selected EOVs required for the assessment of deep-ocean conditions for the DOOS. Following community review[1], these were considered further at a scoping workshop in late 2016. Variables were assessed regarding how well they would serve the challenges posed by deep-ocean science and society (see Section "Scientific Need for Globally Integrated Deep-Ocean Observing" and **Box 2**) and the extent to which GOOS EOVs already covered them. The group also considered specific deep-sea phenomena that required unusual spatiotemporal coverage and resolution, as well as suitable platforms and sensors, and confirmed the need for a deep-ocean component as part of the EOV process that supports GOOS.

The EOV processes of the FOO are based on lessons learned from the global climate observing community, which had great success organizing its efforts around essential climate variables (ECVs). ECVs are physical, chemical or biological variables or a group of linked variables that critically contribute to the characterization of Earth's climate. The Global Climate Observing System (GCOS) currently specifies 54 ECVs (Bellward et al., 2016) required to support the work of the UN Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). Applying the concept of EOVs to ocean observations has considerable conceptual overlap among ECVs introduced by GCOS, the Essential Variables defined for meteorological services by the World Meteorological Organization (WMO) Resolution 40 (Cg-XII), and the Essential Biodiversity Variables (EVBs) as defined by the global biodiversity observing system The Group On Earth Observations Biodiversity Observation Network (GEO BON).

[1] http://www.deepoceanobserving.org/reports/consultative-report/

TABLE 1 | International policy-making bodies, initiatives and agreements that either require or would benefit from deep-ocean observations.

Theme	Body or Convention	Goals	Links to the Deep Ocean
Climate	United Nations Framework Convention on Climate Change (UNFCCC)	An intergovernmental treaty developed to address the problem of climate change	Climate change cannot be understood without an improved understanding of ocean processes and sinks
	Paris Agreement	An agreement to reduce carbon emissions and limit warming	Requires a broader understanding of deep-ocean processes
	Intergovernmental Panel on Climate Change (IPCC)	Scientific body to provide information to policy makers; summarizes ocean changes and consequences; Prepares assessment reports and special reports	The deep ocean vulnerabilities and roles in climate mitigation are increasingly recognized, including in the *Special Report on Ocean and Cryosphere*
	Sustainable Development Goal 13	Take urgent action to combat climate change and its impacts	The deep ocean requires a higher profile in SDG 13
Biodiversity	SDG 14 (Life Below Water)	Calls for, among other things, an increase in scientific knowledge, covers pollution, sustainable fisheries, ocean acidification	DOOS has teamed up with DOSI and INDEEP (scientific networks) to build global scientific capacity to address SDG 14 targets as they relate to the deep ocean
	The UN Decade of Ocean Science for Sustainable Development 2021–2030	Addresses the ocean science needed to implement SDG 14	The deep ocean has a major role to play in each of the Decade R and D priority areas
	UN Intergovernmental Conference to negotiate the new Biodiversity Beyond National Jurisdiction (BBNJ) instrument	Negotiations to develop a new treaty for biodiversity beyond national boundaries. Elements include Area-based management tools including MPAs, Environmental Impact Assessment, Marine Genetic Resources, and Capacity building and technology transfer	Deep-ocean observing can contribute to each of the key elements, informing on connectivity, habitat suitability and more
	Convention on Biological Diversity	Calls for *in situ* conservation of marine and coastal biodiversity as well as more general sustainable use. Has spearheaded the description of Ecologically and Biologically Significant Areas (EBSAs) in marine and coastal waters	A specific program of work focused on impacts of ocean acidification and other stressors in cold water ecosystems. Deep-ocean observing can contribute to EBSA designation and development
Deep Seabed Mining	International Seabed Authority (ISA)	Oversees seabed mining activities and protection of the marine environment from mining impacts	Will need to assess, predict and control mining impacts entailing an understanding of the impacts of climate change on the deep ocean
Fishing	Food and Agriculture Organization, Regional Fisheries Management Organizations (RFMOs)	RFMOs designate Vulnerable Marine Ecosystems (VMEs) and fishing grounds for demersal fisheries	New fisheries require environmental impact assessments, and will need to consider broader impacts of climate change
	UN Agreement on Highly Migratory and Straddling Fish Stocks	Aim to sustain shared fisheries, while protecting biodiversity in the marine environment	Will need to understand how deep-ocean changes affect health and resilience of fish stocks, biodiversity and associated marine ecosystems
	Convention on Migratory Species	Coordinating initiatives to safeguard highly migratory species	Will need to understand how deep-ocean changes and human activities in the deep ocean affect migratory species
	Regional Seas Organizations (RSOs)	Regional platforms to coordinate policies and activities related to conservation and sustainable development	Considerable deep ocean lies within regional seas jurisdiction
	UN Environment Program	Coordinates many ocean and coastal programs, initiatives and agreements, including on land-based sources of marine pollution, regional cooperation and marine debris	The deep ocean is recipient of much land-based pollution and marine debris
Shipping and **Dumping**	International Maritime Organization (IMO)	Adopts global regulations to manage merchant shipping, dumping from sea and geoengineering in the ocean	Activities and environment are both increasingly vulnerable to climate change
Ocean Assessment	UN Regular Process for Global Reporting and Assessment of the State of the Marine Environment	Created the Global Integrated Marine Assessment (World Ocean Assessment-1) that demonstrated the need for sustained ocean observations to monitor and understand ocean change. A second integrated ocean assessment process is now underway (WOA-2) with emphasis on recent change in knowledge and human activities relative to ocean sustainability	Ocean sustainability and health will be fundamentally affected by deep-ocean changes from rising CO_2 emissions and direct human impacts

Noting that EOV selection is an ongoing, iterative process, we discuss key variables below. The FOO requires that EOVs can be observed or derived on a global scale, and are technically feasible using accessible, well-accepted methods. Levels of readiness in developing EOVs differ across the three disciplines, pointing to a need to bring relevant deep-ocean requirements, variables, technologies, and data products with a low readiness level from "concept" to "maturity." In particular, many biodiversity and ecosystem EOVs developed for shallow-water environments are not relevant for deep water and the status, maturity level, and ubiquity of EOVs for all disciplines often differ between shallow and deep water.

Physics

Deep-ocean physical science gaps include: deep-ocean circulation, ventilation rates and their variability, meridional overturning circulation, deep-ocean warming and freshening, impact on patterns of sea level rise, abyssal mixing, ocean bottom boundary layers and their representation in ocean climate models, and geothermal heating. To close these knowledge gaps, we must quantify flow velocity, density (T, S, r), and pressure variations in space and time as well as turbulent stresses, bottom boundary conditions, and seafloor geometry. Four existing EOVs capture the subsurface state. Sea surface height, an integrating (whole water column) measurement, connects intimately with ocean bottom pressure (OBP) as well as deep temperature and salinity (density) measurements. EOVs already include subsurface temperature, salinity, and currents. Proposed new EOVs include OBP, ocean turbulence, and ocean bottom boundary fluxes (**Table 2**).

Ocean bottom pressure

Ocean bottom pressure observations are necessary to understand causes of sea level rise specifically related to changes in mass due to circulation changes (locally) and land ice drainage (integrated globally). Distributed OBP sensors can define how water column mass varies geographically, helping to validate climate change model predictions and support satellite remote-sensing missions, e.g., the Gravity Recovery and Climate Experiment (GRACE) and its follow-on (GRACE-FO) mission. Unlike remote sensing approaches, distributed OBP sensors can provide high temporal resolution, as well as a better horizontal resolution.

Bottom pressure measurements, particularly on the global continental slope, can monitor ocean circulation important for global-scale ocean variability and climate. GOOS should prioritize such measurements (Hughes et al., 2018). At high frequencies, OBP is sensitive to barotropic tides, internal waves and tides, infragravity waves, storm surges and tsunamis. De-aliasing many other measurements, especially those from satellites, requires accurate determination of tidal constants (and secular changes). OBP observations contribute directly to tsunami early warning, a critical task for GOOS.

Self-calibration of modern OBP sensors increases the value of observations by eliminating long-term drift that severely hampered their use for studying interannual and longer time scale variability (Sasagawa and Zumberge, 2013; Kajikawa and Kobata, 2014). The Ocean Observations Panel for Climate (OOPC) has approved OBP as an emerging EOV.

Ocean turbulence

Oceanic tracers exist in an advective-diffusive balance. Diffusion is ultimately achieved through micro-scale mixing, which plays a central role in the formation and modification of water masses, the distribution and flow of heat, and relates to biological populations and processes, e.g., by providing nutrients and oxygen. Mixing processes play a central role at many stages of the Earth's carbon cycle. de Lavergne et al. (2016a) argue "that the largely unchartered bottom boundary waters are as central to ocean functioning as their surface counterparts." The lack of understanding of deep-ocean processes, especially mixing and dissipation, may be the main challenge to further progress, becoming a bottleneck to a truly adequate understanding of ocean circulation and climate on the time scales commensurate with human society (Naveira Garabato, 2012).

TABLE 2 | Global Ocean Observing System (GOOS) Essential Ocean Variables (EOVs) and new EOVs proposed by the Deep Ocean Observing Strategy (DOOS).

	Physics	Biogeochemistry	Biology and Ecosystems
GOOS EOVs	Sea state	Oxygen	Phytoplankton biomass and diversity
	Ocean surface stress	Nutrients	Zooplankton biomass and diversity
	Sea ice	Inorganic carbon	Fish abundance and distribution
	Sea surface height	Transient tracers	Marine turtle, bird, mammal abundance and distribution
	Sea surface temperature	Particulate matter	Hard coral cover and composition
	Subsurface temperature	Nitrous oxide	Seagrass cover
	Surface currents	Stable carbon isotopes	Macroalgal canopy cover
	Subsurface currents	Dissolved organic carbon	Mangrove cover
	Sea surface salinity	Ocean color	Ocean sound
	Subsurface salinity		Microbe biomass and diversity (emerging)
	Ocean surface heat flux		Benthic invertebrate abundance and distribution (emerging)
EOVs under consideration by DOOS	Ocean Bottom Pressure	Seafloor labile organic matter	Body size
	Seafloor Fluxes	Seafloor respiration	Seafloor sponge habitat cover
	Ocean Turbulence	Seafloor fluid and gas effluxes (focus on methane)	Connectivity of species
		Litter including microplastics	

Several studies demonstrate the relevance of mixing for large-scale oceanic processes (Wunsch and Ferrari, 2004). Incorporation of a very simple bottom-enhanced mixing eddy diffusivity into existing climate models results in a major change in predicted deep ocean structure (MacKinnon et al., 2017). Existing parameterizations that relate fine-scale variability (5–100 m) to mixing are known to be in error at intense topographic mixing sites (Klymak et al., 2008). The challenge is to develop parameterizations that remain accurate through major departures from our present climate. It is clear that deep mixing will vary as stratification and bottom currents change (Melet et al., 2016). Observations required to quantify these effects are needed. While numerous techniques exist to map the flow of the ocean, the ability to directly measure ocean mixing has been gained only recently. The ability to routinely collect the microscale observations necessary to infer ocean mixing is emerging rapidly. Future global ocean observing programs must recognize rapidly developing methods and the cost effectiveness of incorporating microscale sensing systems into existing observational assets (**Figure 2**). Understanding the co-variability of chemical, biological, and physical parameters across a wide range of space and time scales will provide great scientific and societal benefit.

Bottom fluxes

Despite small hydrothermal flux of water (0.005 Sv estimated) relative to all other boundary fluxes, geothermal heat flux (GHF) from the Earth's interior to the oceans globally averages ∼100 mW/m^2, although with large variation (Davies, 2013). The average level is significant compared to the global net radiative imbalance of ∼500 mW/m^2 (Stephens et al., 2012), corresponding to a mean temperature change of 0.01°C in a decade (Wunsch, 2016). As we accumulate data records longer than decades, accounting for bottom geothermal flux, including spatial and temporal variability, will be necessary. Heat fluxes can destabilize the density profile at depth, facilitating mixing, and are comparable to internal wave and lee wave dissipation in terms of energy dissipation and the mixing of deep waters. Ocean bottom GHF is about 28 TW; assuming even a few percent efficiency in conversion to mechanical energy, puts GHF on the same level as tides (∼1–2 TW; de Lavergne et al., 2016b). Few of today's ocean circulation or climate models account for these geothermal fluxes (e.g., less than half in the intercomparison study by Griffies et al., 2014), but modeling groups are beginning to assess more rigorously the impact of geothermal fluxes on large-scale ocean circulation (e.g., Mashayek et al., 2013; Piecuch et al., 2015). The DOOS EOV Task Team is considering a long-term plan for observing heat and mass flux.

FIGURE 2 | A Chi-Pod package configured for moored deployment (Courtesy Jim Moum, OSU).

Comprehensive and sustained observation of deep- and bottom-water formation processes in key regions of water mass transformation (e.g., in polar regions) is an ongoing challenge in both hemispheres, with remaining surprises that challenge conventional depictions of the global overturning circulation, both in terms of their source regions (e.g., Lozier et al., 2019) as well as their abyssal component (de Lavergne et al., 2017). Equally challenging remains their adequate representation in ocean climate models (e.g., Lohmann et al., 2014; Snow et al., 2015, 2016).

Biogeochemistry

The deep ocean plays a critical role in global biogeochemical cycles and hosts key marine ecosystem functions and services, e.g., in terms of carbon sequestration or nutrient regeneration for sustained oceanic productivity (e.g., Thurber et al., 2014). It contains over 90% of the labile carbon and inorganic nutrients residing in the Earth system and increasing atmospheric carbon dioxide levels and other global climate change-related and anthropogenic impacts affect deep-water ecosystems (e.g., Ramirez-Llodra et al., 2011; Levin and Le Bris, 2015). Changes in surface water productivity, deep-water respiration and remineralization, and circulation and mixing of the deep ocean all affect carbon cycling, as well as oxygen and nutrient levels (e.g., Talley et al., 2016). Most key biogeochemistry-centered questions (**Box 2**) relate to the deep ocean's ability to store carbon dioxide drawn from the atmosphere to mitigate anthropogenic carbon emissions, either by direct uptake via the ocean surface and physical transport to the ocean interior (i.e., solubility pump) or by uptake through biomass export to depth for long-term residence in the deep ocean or ultimate sequestration in deep-ocean sediments (i.e., biological pump). The uptake of inorganic carbon or its release upon remineralization of organic matter leads to changes in ocean chemistry, i.e., pH and carbonate ion concentration, which in turn may affect biogeochemical processes in deep waters (e.g., Sarmiento et al., 1998; Feely et al., 2009). Hence, there is a strong need to extend routine observations to the deep-water column and to the deep seafloor to assess the biological pump as a key process with a particularly strong deep-ocean component (e.g., Muller-Karger et al., 2005; Honjo et al., 2014). Important biogeochemical

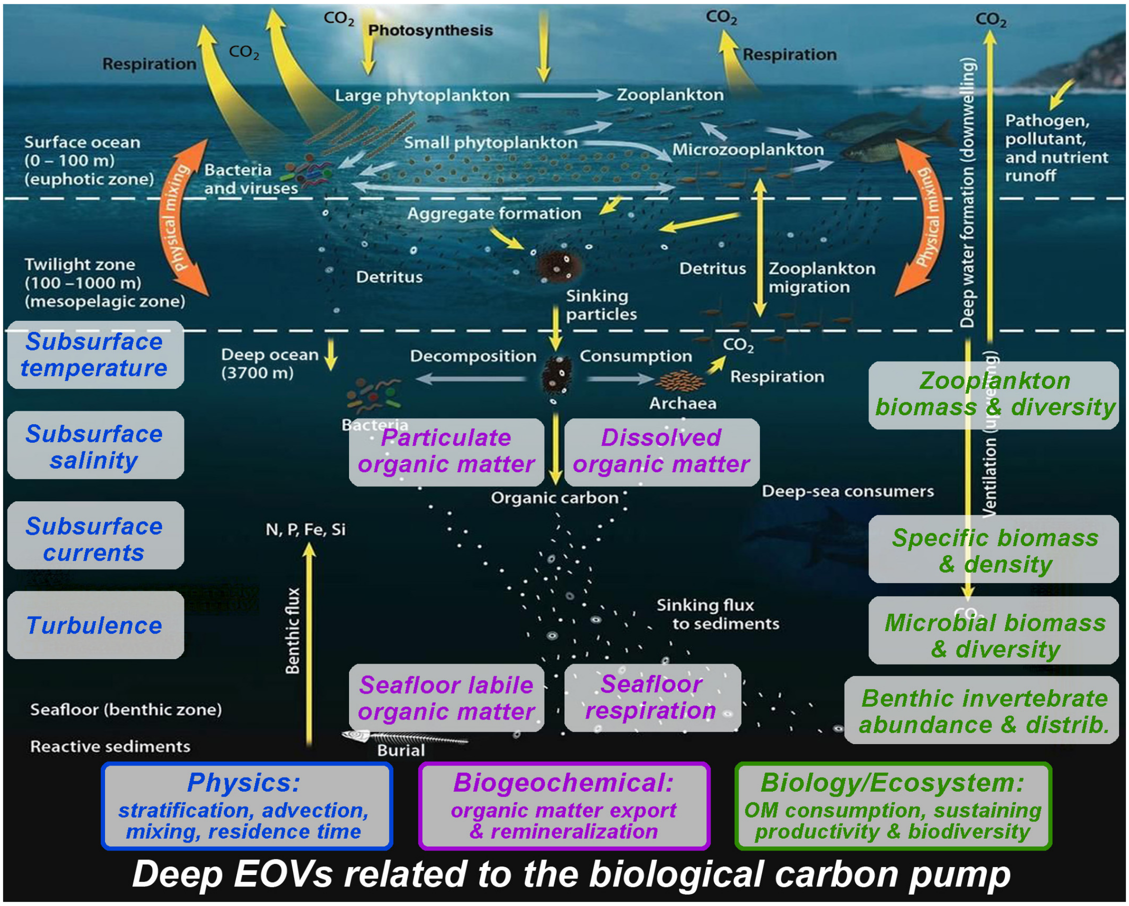

FIGURE 3 | Multidisciplinary observations throughout the water column are necessary to fully address the biological pump. Information that can be derived from EOVs: *Physics:* stratification affects particle sinking; understanding the origin of the particles and the residence time of the DIC from particle remineralization in the deep ocean requires measurement of advection and mixing. *Biogeochemistry:* export/mixing down of particulate and dissolved organic matter from the surface layer determines labile organic matter arriving at the seafloor, which is either respired by seafloor biota or stored for longer times in the sediment. *Biology and ecosystems:* zooplankton and microorganisms break down and remineralize sinking particles in the water column. Exported organic matter feeds all water column and benthic biota (zooplankton, benthic invertebrates, microbes) sustaining their biomass, density, and biodiversity. Background Image: U.S. DOE. 2008. Carbon Cycling and Biosequestration: Report from the March 2008 Workshop, DOE/SC-108, U.S. Department of Energy Office of Science, https://genomicscience.energy.gov/carboncycle/report/.

variables to quantify the efficiency of biological pump transfer of carbon dioxide from the atmosphere to the deep ocean include remineralization rates and solute fluxes at the sediment-water interface, as well as redox conditions in sediments and deep waters. A review of deep-ocean biogeochemical EOVs emphasizes development and review of sensors for deep-ocean particle fluxes, seafloor labile organic matter, and seafloor respiration rates, in the context of assessing the biological pump (**Figure 3**).

Sensors to observe multiple variables have matured, but not always at the precision required to assess potentially small and slow natural variability and trends in the deep ocean. The recent list of EOVs specified by the GOOS biogeochemical expert panel encompass most of the biogeochemical EOVs suggested in the DOOS consultative report: inorganic carbon and its isotopic composition, nutrients, oxygen, particulate and dissolved organic matter (**Table 2**).

Characterizing spatial, seasonal, and inter-annual variability in bathypelagic flux characteristics requires sustained observations both with traditional moored particle traps as well as novel instrumentation for high resolution observations (e.g., particle cameras, optical sensors) deployed with novel platforms (e.g., neutrally buoyant, drifting particle traps). Constraining the supply and ultimate fate of organic matter at the bottom of the ocean requires time series of detritus deposition and respiration rates at the seafloor using moored or mobile platforms (e.g., Smith et al., 2017). The turnover time of DOM at varying depths and temperatures will affect carbon sequestration and calls for *in situ* measurements of DOM concentrations and turnover along with concurrent observations of DOC and ocean microbiome characteristics (e.g., Moran et al., 2016). Key factors determining ocean health and productivity link to the transport of organic matter to the ocean interior, deep-water oxygenation and nutrient pools. Most life in the ocean requires oxygen, hence predicting biological response to climate change requires understanding the nature and causes of oxygen variation (e.g., Keeling et al., 2010; Friedrich et al., 2014). Ocean warming-induced changes in solubility, stratification, ventilation, other wind-driven local hydrodynamic forces, and respiration drive global declines in oxygenation, even in the open and deep ocean (e.g., Stramma et al., 2008; Helm et al., 2011). Assessing oxygen variability over seasonal to decadal time scales and the longer-term secular oxygen trends in the deep ocean (Levin, 2018) requires long-term observations e.g., with moored oxygen sensors and deep Argo floats equipped with oxygen sensors. New technologies (e.g., optical and Lab-on-a-chip sensors and biogeochemical Argo floats) offer high resolution nutrient measurements to resolve deep-ocean nutrient pools and their dynamics in order to address open ocean productivity and its changes – including feedback to the biological carbon pump. In addition, measurement of bioturbation, seafloor fluid and gas/methane efflux at key locations, as well as microplastics could clarify deep-sea biogeochemical processes, human pressures on deep sea ecosystems, and the role of the deep sea as a potential source for greenhouse gases.

Biology and Ecosystems

The GOOS has identified biological and ecosystem EOVs for implementation in a sustained, global observing system (**Table 2**). The many dimensions of biology and ecology and the associated challenges with the multitude of approaches for quantitative measurement, sampling, and data management added significant complexity to this task. Given the complexity of marine ecosystems and the challenge of selecting key variables, GOOS used a Driver-Pressure-State-Impact-Response (DPSIR) model with input from surveys and literature searches to prioritize variables (Miloslavich et al., 2018). This process also considered key societal drivers including sustainable use of natural resources, biodiversity conservation, and knowledge; environmental quality and threat prevention and mitigation; capacity building, sustainable economic growth, and ecosystem-based management; and food security. It also considered the need to identify which scientific and societal needs require sustained biological and ecological oceanographic observations, as well as examining impact and feasibility (Lindstrom et al., 2012).

The GOOS also identified EOVs to assess impacts of major pressures related to the deep ocean including habitat loss, climate change, pollution (including debris and litter), solid waste disposal, ocean acidification, and direct anthropogenic disturbances, e.g., connected to fishing, hydrocarbon and seafloor mining industries (Ramirez-Llodra et al., 2011; Ruhl et al., 2011). Reviewing EOVs indicated GOOS specifications that could be easily evolved to include a deep-sea context, including hard coral cover and composition, zooplankton biomass and diversity, fish abundance and distribution, ocean sound, microbial biomass and diversity (emerging), and benthic invertebrate abundance and distribution (emerging). Indeed, the GOOS EOVs now include most of the DOOS recommendations, either as direct EOVs, variables derived from existing EOVs (e.g., biodiversity metrics), or as supporting variables identified in existing EOV specifications.

The designation of marine protected areas and vulnerable marine ecosystems that influence fishery operations often invoke special regulations for deep (cold-water) corals (e.g., Huvenne et al., 2016), although other forms of living habitat merit consideration, including sponge grounds (e.g., Konnecker, 2002; Beazley et al., 2013). Beyond existing EOVs, body size defines a key feature for ecological understanding and represents a fundamental macroecological structuring feature, *sensu* the Metabolic Theory of Ecology (e.g., Brown et al., 2004). The utility of body size information in forming budgets of the stocks and flows of carbon, as well as understanding several basic physiological dimensions, makes body size a valuable EOV consideration. EOVs that measure aspects of connectivity of species between locations also merit consideration. Connectivity has been identified as a key variable in designing marine protected area networks and in understanding how areas impacted by human disturbances might recover (e.g., from seabed mining, Vanreusel et al., 2016; Durden et al., 2018). The presence of a particular taxon at specific locations, effectively an existing EOV, can indicate connectivity. However, information on movement of individuals (e.g., Block et al., 2011) and genetic variation adds considerable information on the degree to which different populations might be connected by various forms of dispersion.

The GOOS and DOOS efforts on EOVs for biology and ecosystems are informed, in part, by the efforts of GEO BON. This international network has several regional and national component projects including the Marine Biodiversity Observation Network (MBON) projects contributing to the US Integrated Ocean Observing System (IOOS) or the European Biodiversity Observation Network. GEO BON efforts have included the specification of EBVs (Muller-Karger et al., 2018).

Critical to the success of the GOOS EOV concept is the ability to discover, access, share and analyze these data. For some disciplines, this is already operational at a mature level, such as with temperature data being reported through the Global Telecommunication System and assimilated into weather forecast models. Biology and ecosystem data sit in a relatively developmental stage. However, the vision of machine readable "big data" for biology is being realized for the ocean at a global level with the maturation of the Darwin Core body of metadata standards (De Pooter et al., 2017) and their application in data being made available through globally important data portals such as the OBIS (Grassle and Stocks, 1999) using ontologies of the World Register of Marine Species (WoRMS; Horton et al., 2017).

New and Expanded Synergies Among Stakeholders

To address the breadth of scientific questions and societal needs that require sustained deep-ocean observing, it will be necessary to engage a broader suite of practitioners and approaches. In addition to traditional scientific community operations, a growing number of organizations, industries, and individual businesses are now engaged in the collection of relevant deep-ocean data. A successful global deep-ocean observing system will need to capture those data, coordinate that nascent network of observatories, and help guide its further development. Below we highlight several opportunities for new and expanded synergies among the various members of the extended deep-ocean observing community.

Industry

Oil and gas

The offshore energy industry invests considerable resources into data collection from the deep oceans throughout the life of an oil field, from exploration to decommissioning. In exploration this includes high-resolution acoustic (Posamentier and Kolla, 2003) and electromagnetic (Constable and Srnka, 2007) mapping of oil reservoirs, fields and the surrounding sedimentary environment to inform subsequent development, the siting of infrastructure including pipelines, and the identification of potential geohazards. The industry is also required to collect environmental baseline data and to carry out environmental monitoring in order to secure the license to operate. Those data are used to support the EIA and to ensure continuing appropriate environmental management. If appropriately archived and discoverable, these data are of considerable value to deep-ocean observing and broader scientific interest in the deep-sea floor.

While academic recognition of oil and gas industry environmental impacts is widespread (Cordes et al., 2016), the industry collaboration with the academic community is long-established and, in some areas, very highly developed. Multi-partner collaborations on both the industry and academic side have been successful in tackling regional issues (Bett, 2001), but there is clear scope for expansion to basin- and global-scale efforts. There is genuine mutual benefit in these collaborations, including improved survey, monitoring, and observing approaches, increased data value and decreased costs to individual operators, and ultimately increased spatial and temporal resolution in our deep-ocean observations (Jones et al., 2014). A simple but effective ongoing collaboration with global reach is the Scientific and Environmental ROV Partnership using Existing iNdustrial Technology (SERPENT) project. This project operates by accessing unused Remotely Operated Vehicle (ROV) capacity to acquire deep-ocean data with added value. To date SERPENT has run over 125 missions to deep-water locations in Europe, North and South America, Africa and Australia and generated over 50 peer-reviewed scientific papers (e.g., Hoving et al., 2013; Higgs et al., 2014; McLean et al., 2017; Macreadie et al., 2018).

There are numerous examples of other successful short-term collaborations investigating a range of key questions, including: extent of anthropogenic impacts (Netto et al., 2010); recovery from anthropogenic impacts (Jones et al., 2012), role of infrastructure (Bond et al., 2018); potential impacts on reef-forming corals (Purser, 2015), and characterization of local biodiversity (Jamieson et al., 2017). In the deep-ocean observing context, long-term collaborations are a key focus for further expansion of these synergies. Early examples include the pair of Deep-ocean Environmental Long-term Observatory System (DELOS) seafloor observatories installed in a deep-water (1400 m) oil field on the Angola Margin in 2009 (Vardaro et al., 2013), which provides publicly accessible data through a series of scientific collaborations. DELOS adopts a "control-impact" long-term monitoring approach, with one observatory immediately adjacent to oil and gas seabed infrastructure, the second some 16-km distant. The Lofoten-Vesterålen (LoVe) cabled seafloor observatory is located on the deep (258 m) Norwegian Shelf, with plans for subsequent extension to deeper water (Godø et al., 2014). The LoVe observatory was situated in an area of strongly "competing" interests: oil and gas development, fisheries, and biodiversity, a key focus of which has been reef-forming corals (Osterloff et al., 2016). The data from the LoVe observatory is made available publicly in real time. Environmental data associated with oil and gas activities is typically not regarded as being commercially important and hence can usually be shared. These two examples of industry observatories, while focused on specific regions, demonstrate the potential for such infrastructure to enhance environmental management and generate data of direct operational use to industry. Furthermore, such infrastructure may be installed at modest additional cost to industry if it is done during the right point in the field development, providing continual high-resolution data that would otherwise be expensive to obtain.

Installation of deep-water observing nodes at all regional centers of oil and gas activity could improve survey, monitoring, and observing approaches, increasing the value and decreasing the cost of such efforts to industry and increasing spatial and temporal comparability. Data and samples collected as part of science-industry collaboration could then be of greater value to industry, regulators, and academic researchers to address questions beyond the industrial requirements (e.g., Jones et al., 2014), for example insights provided into the ecology of deep-sea organisms (Hoving et al., 2013; Higgs et al., 2014) and enhancing the social license to operate (**Box 3**).

Fisheries

Deep-sea habitats provide key feeding grounds, spawning grounds and nursery grounds (seamounts, cold water coral reefs, canyons, seeps) for fish increasingly targeted by commercial fisheries (Watson and Morato, 2013). Fisheries vessels could offer potential research platforms[2], given that fishers offer the necessary skills and experience to deploy and recover diverse scientific equipment spanning from specialized cameras on longlines (Welsford et al., 2014) to sophisticated acoustic systems that support seabed mapping (Wynn et al., 2014).

Vessel monitoring system (VMS) data can show how fisheries utilize the deep sea and the status of deep-sea target species (Bueno-Pardo et al., 2017), however, VMS data are often confidential. Fishers often resist providing data or Remote Electronic Monitoring, fearing increased restriction on operations by regulators (e.g., creation of Marine Protected Areas). Nonetheless, the many fishery vessels globally could greatly enhance deep-sea data collection and monitoring, perhaps through involvement in global VME mapping, documenting fish distributions, tools to log unusual species (potentially aiding discovery of new ecosystems), or attaching loggers to fishing gear to characterize environments (as in Keller et al., 2015). High

[2] https://www.scotsman.com/news/opinion/it-s-just-a-net-waste-to-ignore-fishermen-1-3715118

BOX 3 | Case study – Ocean observing and the social license to operate.
In the late 1990's NGOs raised concerns about whether offshore energy companies were being responsible custodians of the deep-ocean environment, arguing that they could not observe activities in the deep ocean as they could on land. The oil and gas sector was also concerned that if they were unable to prove their operations were environmentally sound then they may lose their license to operate. This led to some oil and gas operators (e.g. BP DELOS) installing deep-ocean observatories near their operations and making data publicly available. Twenty-five years later, the oil and gas sector is again being asked to be more transparent in their operations to be better corporate citizens with regards to climate change. Observation of both physical and biological changes by this sector in the deep oceans and their linkage to increases in greenhouse gases are increasingly seen as necessary to increase long-term corporate performance by reducing company risks (asset, environmental, etc.) and financial unknowns (production, operability, etc.).

Partnerships between scientists and the offshore energy industry are particularly beneficial for ocean observing owing to the complementary skills and resources of both groups. Ocean scientists offer knowledge on a broad range of physical and biological aspects of deep-ocean ecosystems that are relevant to industry operations but may not typically be available within industry, while industry offers operational expertise that is essential for observation in the offshore environment, as well as in-kind resources including observational platforms (i.e. fixed infrastructure) and transportation (i.e. vessels) that are typically not feasible for independent scientific investigation (Gates et al., 2017). Further efficiencies can be generated during ongoing partnerships through training of offshore personnel in scientific observational protocols. Such ongoing partnerships and the accelerated knowledge of marine ecosystems they facilitate are key to sustainable growth in the offshore energy sector.

value fisheries with resources and observer programs offer a particularly good opportunity for engagement.

Mining

The deep ocean contains massive reserves of commercially important minerals, particularly metals (Miller et al., 2018). Currently most of these resources remain untapped. However, exploration activities and commercial interest is increasing. Areas of mining interest occur around the world for a range of resources, including in remote areas and abyssal depths. These resources include polymetallic nodules, typically found on abyssal plains; seafloor massive sulfides, created by hydrothermal activity at mid-ocean ridges and back-arc basins; and cobalt-rich crusts, which occur in highest densities on seamounts (Levin et al., 2016; Cuyvers et al., 2018).

The mining industry is expanding, and deep-sea contractors are currently in the exploration phase. Deep-ocean data on a wide variety of parameters are necessary for establishing the commercial and social viability of projects. Baseline data on the biological, physical and chemical environment are required for management and to secure the permits for mining activities (Durden et al., 2018).

As the impacts of mining activities in the deep ocean are expected to be extensive in space and time (Jones et al., 2017), evaluations of impact and recovery from experiments and early mining activities are also critical to inform management and set the policy framework for future exploitation activities. This is particularly critical in the case of mining activities beyond national jurisdiction, where the International Seabed Authority has a remit under the UN Convention on the Law of the Sea to prevent serious harm to the marine environment (UNCLOS, 1982). As a potentially global industry in its infancy, with internationally coherent regulations, environmental measurements associated with environmental management of deep-sea mining offers great potential to increase the frequency and extent of deep-ocean observations to the benefit of both the mining industry and deep-ocean science. The ISA is already taking action to harmonize the data provided by its contractors as part of exploration activities to enhance the amount of regional deep-ocean data available. As mining companies move to exploitation, have greater presence in the deep ocean, and begin monitoring activities, the data collected will increase in volume. At present, most data are obtained from individual shipboard expeditions or regular cruise programs. Some physical oceanographic data have been obtained by moorings, put in place for up to 3 years (Aleynik et al., 2017). As yet, the only truly multidisciplinary, deep-water seafloor observatories in areas of potential mining interest are on the mid-Atlantic ridge (e.g., the MoMAR observatory at Lucky Strike; Ballu et al., 2008). Furthermore, long-term seafloor or water column observatories and integrated multi-stakeholder cruise programs would result in improvements in the temporal and spatial extent of ocean observations.

In the context of exploration activities, strong bilateral partnerships exist between specific contractors and scientific institutions. Actions that might promote cooperation on a broader level, e.g., as part of international academic-industry partnerships, as described above for the energy industry, could involve the creation of multi-stakeholder regional working groups focused on areas that have been targeted for mining like the Clarion Clipperton Fracture Zone, mid-Atlantic or Southwest Indian Ridges or West Pacific seamounts. These could work through existing networks (e.g., DOOS or DOSI, ISA or World Ocean Council) to coordinate among the different stakeholders or integrate sustained academic observing network efforts (e.g., Argo floats, including Deep and BCG Argo, Go SHIP, OceanSITES, GeoTRACES, and/or TPOS 2020) with industrial observing programs and environmental monitoring needs, possibly as demonstration projects or observatories. A better integration with large-scale marine scientific networks would add credibility to industry and its activities. It may also facilitate integration among different contractors to allow for ecosystem observations beyond claim areas, as they are urgently needed for environmental assessment and management at the relevant scales (e.g., in the context of Regional Strategic Environment Assessment and Regional EMPs).

Ships at sea

Many types of commercial vessels can be used as "ships of opportunity" to provide additional platforms for oceanographic observation. This approach has a very long history that can be traced to Robert FitzRoy, captain of HMS *Beagle* during Charles Darwin's voyages, who would later found the forerunner of the UK Meteorological Office by organizing the collection of weather data at sea, and the provision of standard instruments to those vessels (Mellersh, 1968). In the upper ocean, the longest-running effort is the Continuous Plankton Recorder (CPR)

Survey[3]. Since its first deployment in 1931 by its inventor Sir Alister Hardy, it has covered over 6.5 million nautical miles (12×10^6 km). Standardized vessel-mounted instrumentation has proved successful for surface-ocean biogeochemistry data collection, for example the "Ferrybox" program (Hartman et al., 2014; Petersen, 2014). The ferry (= ship of opportunity) box (= instrument package) concept may be particularly valuable in monitoring substances, including pollutants and contaminants, that are currently difficult or impossible to detect with self-contained autonomous instruments (see e.g., Brumovskι et al., 2016). Surface vessels, however, offer relatively limited opportunities for deep-ocean observations beyond bathymetric data, which may nonetheless be significant to the extent that the International Hydrographic Office has established a Crowdsourced Bathymetry Working Group[4]. An obvious exception is the deep-water fishing fleet (discussed above), for whom recovery of deep-ocean "samples" is normal operating procedure.

Submarine cables

The increase in demand for both global connectivity and deep-ocean data is creating strong synergy between the submarine telecommunications cables industry and the ocean observing community. Emerging out of this shared demand is the concept of "Science Monitoring and Reliable Telecommunication" (SMART) cables, dual-purpose cables in which scientific sensors "piggyback" on the undersea cables, allowing them to generate real-time oceanographic and seismic data in addition to performing their primary telecommunications mission (You, 2010). The International Telecommunication Union, the WMO, and the UNESCO Intergovernmental Oceanographic Commission (IOC) have formed the Joint Task Force (JTF) to move this concept forward (ITU/WMO/IOC JTF[5]). The prospect is seen to be mutually beneficial to both the industry and the science partners, and ultimately of significant value to societal needs not least in relation to climate change, and tsunami and seismic early warning (Howe and Workshop Participants, 2015).

Exploration and Mapping Communities

Knowing the depth, shape and character of the seafloor is fundamental for ocean science and has been identified by the Decade of Ocean Science for Sustainable Development as a major research and development priority for 2021–2030 (IOC, 2018). Seafloor bathymetry is a foundational dataset for understanding ocean circulation, tides, tsunami forecasting, fishing resources, environmental change, underwater geo-hazards, cable and pipeline routing, mineral extraction, oil and gas exploration and development, and infrastructure construction and maintenance. The ocean exploration community collects bathymetry and other initial characterization datasets using a routine, systematic or "mapping" methodology with the objective of making results publicly available and accessible soon after collection. The current ocean exploration survey methodology includes multi-beam bathymetric data collection and making initial observations and assessments of living and non-living marine resources using conventional midwater acoustics and near-bottom imagery and sensing. The ocean exploration mapping survey approach plays a unique role in the discovery and initial characterization of lesser-known areas of the ocean and particularly the deeper regions, which are difficult to access. Even after many years of bathymetric mapping effort, only a small fraction, less than 20 percent, of the world ocean's seafloor has been mapped with modern methods, with even less characterized in any standardized way. Less than 18% of the seafloor has been directly measured with echo sounders and approximately 8% with modern multi-beam methods (Mayer et al., 2018; **Figure 4**). A coordinated international effort is needed to bring together existing ocean data sets and identify areas for future exploration and mapping surveys.

The larger ocean science community, including governments, industry, and academia recognize the need for ocean mapping information and are working together on initiatives to collect new mapping data and to make archived data publicly available in standardized formats. The General Bathymetric Chart of the Oceans (GEBCO) Seabed 2030 Project is an example international effort with the objective of facilitating the complete mapping of the world ocean by 2030 (Mayer et al., 2018). GEBCO is an international group of mapping experts developing a range of bathymetric data sets and data products. It operates under the joint auspices of the International Hydrographic Organization (IHO) and UNESCO's IOC. The project was launched at the UN Ocean Conference in June 2017 and is aligned with the UN's Sustainable Development Goal #14 to conserve and sustainably use the oceans, seas and marine resources.

The Seabed 2030 Project will apply GOOS concepts and establish distributed regional data assembly and coordination centers that will identify existing data from their assigned regions that are not currently in publicly available databases and seek to make these data available. They will also develop protocols for data collection and common tools to assemble and attribute metadata by regional grids using standardized techniques. A Global Data Assembly and Coordination Center (GDACC) will integrate the regional grids into a global grid and distribute to users world-wide. The GEBCO Seabed 2030 Project will encourage and help coordinate and track new survey efforts and facilitate the development of new and innovative technologies to increase the efficiency of seafloor mapping and help to achieve the ambitious goals of the project.

While the GEBCO effort is significant, it is limited to seafloor bathymetry. A similar effort is needed that can be expanded to include a limited set of variables that could be systematically collected and complement bathymetry to provide an initial characterization of the deep-sea environment. The revision of EOVs carried out by DOOS (see above) and community input during OceanObs'19 will help define those variables for the ocean exploration community to adopt and provide increased value to the science community.

Biodiversity and Ecosystem Services

Deep-ocean biodiversity and the services it supports is an increasing focus of both the conservation community aligned

[3]https://www.cprsurvey.org/

[4]https://www.iho.int/

[5]https://www.itu.int/en/ITU-T/climatechange/task-force-sc

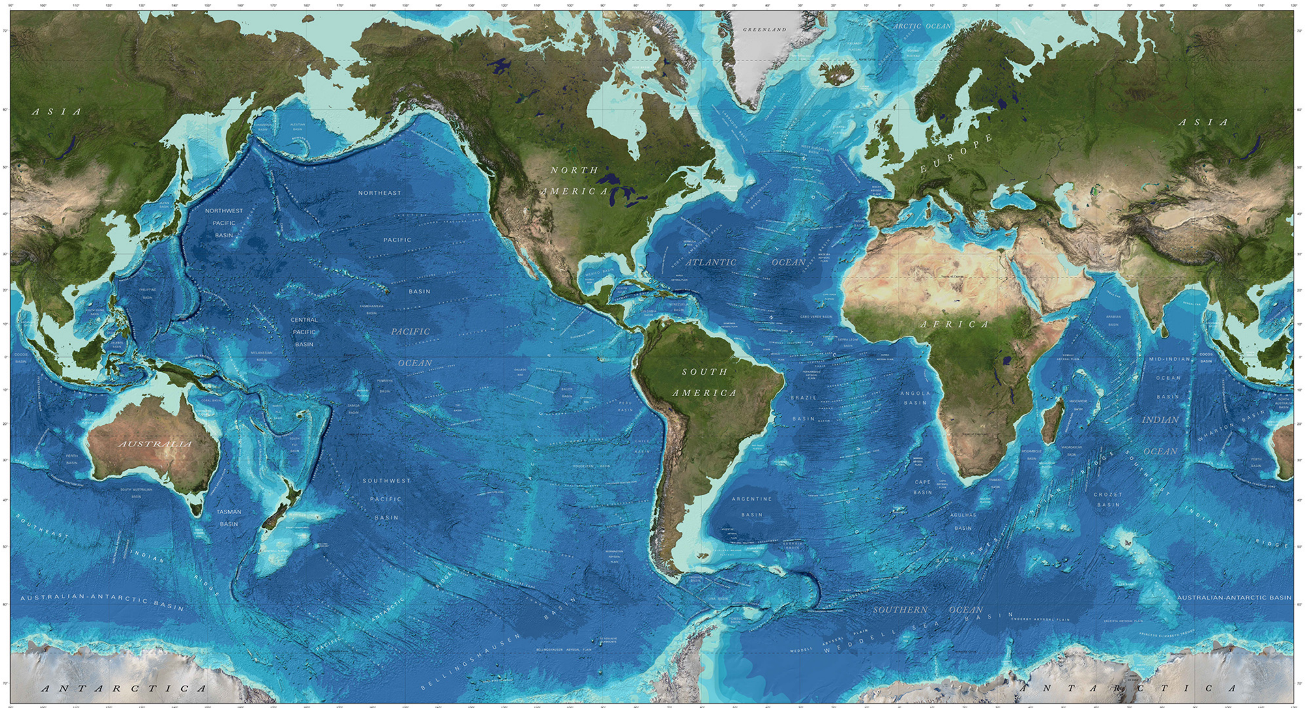

FIGURE 4 | World map of currently available hi-resolution bathymetric data. Image reproduced from the GEBCO world map 2014, www.gebco.net.

with sustainable development and an emerging bioprospecting industry. Deep-ocean biodiversity underpins key support functions and ecosystem services provided by the deep ocean (Duffy and Stachowicz, 2006; Snelgrove et al., 2014). Included among these are the sequestration and burial of carbon, the remineralization and cycling of nutrients, and the provision of habitat, nursery grounds, food, and refugia for living resources (Thurber et al., 2014). Microbial activity contributes to the generation of oil and gas (Rice and Claypool, 1981), polymetallic nodules and crusts (Wang and Müller, 2009), and other potential mineral and energy resources of extractive interest, although these occur on geologic time scales – much longer than what is considered sustainable. Many of these "services" and other natural products can provide a template for novel biopharmaceuticals, industrial agents, and biomimetic materials, with a multitude of realized or potential human benefits (e.g., Blasiak et al., 2018); these are often referred to as genetic resources (Harden-Davies, 2017). Biodiversity, as an irreplaceable entity, also has intrinsic or inherent value, independent of its service to people (Harrington et al., 2010).

A growing mandate for biodiversity observation in the deep ocean emerges not only from human curiosity, but also from a desire for sustainability in the face of intensifying or new human activities that generate disturbance such as bottom fishing, energy extraction, cable laying, and potentially seabed mining (Ramirez-Llodra et al., 2011; Mengerink et al., 2014). These practices, and the negotiation of a new international biodiversity treaty (Wright et al., 2018), are generating a growing need for biodiversity baseline and monitoring data to inform ecosystem-based management, spatial planning and protected area designation, and impact assessment, both at the national and international levels (Danovaro et al., 2016). New stakeholders in deep-ocean biodiversity observation include those entities mandated to protect the marine environment by UNCLOS (**Table 1**, e.g., the ISA, the FAO and RFMOs, the International Maritime Organization, and the Convention on Biological Diversity) as well as industry and civil society. As biodiversity observations expand in the deep ocean, linkages to the MBON of the GEO BON and GEO Blue Planet can help develop the necessary protocols and standards and provide connections between the EBVs of MBON and biology and ecology EOVs (e.g., Muller-Karger et al., 2018).

Reusing and Repurposing Data

Investigators around the world routinely collect, analyze, and publish data for specific studies or to further scientific knowledge in areas of interest. Collectively, these data represent a vast amount of measurements that, more often than not, could be repurposed. Here we describe two examples of the integration between different communities (scientific disciplines, and observation networks, hazard monitoring, offshore industry) that allow for the innovative use of existing datasets for applications other than what was originally intended.

Deep-ocean Assessment and Recording of Tsunami (DART) measurements are routinely made to detect tsunamis in the deep ocean and serve as the basis for warning coastal populations at the time of tsunami propagation. These data represent years, sometimes decades, of consecutive time series of highly resolved pressure and temperature in areas of the deep ocean for which measurements are scarce. Bottom pressure measurements have been repurposed to validate satellite altimetry measurements and improve global tide models (Ray, 2013). Measurements made as part of the GRACE in particular, were instrumental in investigating the main processes that affect variability of pressure in the deep ocean (Chambers and Willis, 2010). Initial comparisons of GRACE-derived bottom pressure (from altimetry) with bottom pressure from the Ocean Model for Circulation and Tides highlighted sampling interval shortcomings that in turn led to both improved data analysis and greater interest in the use of DART bottom pressure sampled every 15 s. Williams et al. (2015) showed the value of long duration and stable bottom pressure records for studies of ocean circulation and ocean mass considerations due to sea level change. In addition to the use of bottom pressure for investigations into ocean processes, recent investigations into the sonification of bottom pressure time series have shown promise in identifying an earthquake signature in advance of rupture (McKinney personal communication). This work follows that of Ballora and Evans (2017) who sonified hurricane data, noting that "our ears are better at sensing properties that change and fluctuate" (Ballora and Evans, 2017). Temperature data recorded by DART systems are being used by investigators for validation of global models and to identify climate variability signatures in the deep ocean. The spatial and temporal scales of use of these data, however, are limited due to a calibration process that prohibits inter-record comparisons. Another example involves assimilation and analysis of the Global Navigation Satellite System (GLONASS) data which are being explored to quantify seafloor displacement as a new approach to rapid characterization of a tsunami source.

Underwater video and still images are routinely collected by ROVs during offshore energy industry operations as part of site surveys and inspections of infrastructure and are usually retained indefinitely by operating companies. Although not intended for scientific research, industry video and images can be repurposed to provide data on a range of biological, ecological and oceanographic variables in areas that are challenging for independent research (Gates et al., 2017). Industry video and images have already provided information on the distribution of threatened species (Gass and Roberts, 2006), productivity of offshore ecosystems for commercial fishes (McLean et al., 2017), and anthropogenic impacts on deep-water fauna (Jones et al., 2012).

Existing media archives could be used to investigate longer-term processes occurring in ocean ecosystems. The offshore energy industry already holds millions of hours of underwater video, covering decades of offshore operation and spanning a broad range of ocean environments, from shallow coastal margins to the deep sea (Macreadie et al., 2018). This collection could be used to investigate the effects of environmental change and anthropogenic disturbance on biological communities, track the spread of invasive species across ocean basins, and ground-truth oceanographic models, among other applications. ROV imaging methods could be refined at minimal cost to provide standardized data on a continual basis, to assist identification of future changes in vulnerable offshore ecosystems (Roberts et al., 2006).

Improved partnerships between researchers and the offshore industries are critical for effective repurposing of data. Industry collects extensive data on the geology, oceanography, and ecology of potential operating sites. Access to these data is often limited by concerns of confidentiality. However, trust developed through ongoing partnerships can increase data-sharing for mutual benefit. By partnering with researchers, industry can add value to data they are required to collect for environmental reporting, and researchers can gain access to datasets that would otherwise be challenging to obtain.

INTEGRATING DISCIPLINES THROUGH DEMONSTRATION PROJECTS

To demonstrate the feasibility of sustained deep-ocean observing, relevant technologies, and the impact and utilization of deep-ocean observations, the DOOS proposes a series of potential region-specific, interdisciplinary projects. These would demonstrate the end-to-end process of deep-ocean observing, data processing, and quality control, as well as ensure availability of data to users with appropriate documentation. Such efforts would advance well-vetted EOVs, state-of-the-art technological capacities, and modular dimensions of associated platforms, projects, and data products. These would provide a template that could ideally scale from local to quasi-global coverage. We summarize key features, science questions, societal relevance and infrastructure for each of these candidate projects (**Table 3**) and provide brief, relevant background.

Clarion-Clipperton Zone

The Clarion-Clipperton Zone (CCZ), an abyssal area between the Clarion and Clipperton fractures, with polymetallic nodule mining potential in the central eastern Pacific (Lodge et al., 2014), covers six million km^2 at water depths between 3800 and 6000 m. All seventeen deep-sea mining contractors with exploration claims in the CCZ must collect and provide physical, chemical and biological data to the ISA. Although oceanographic moorings have been deployed there for up to 3 years (Aleynik et al., 2017), the CCZ lacks any long-term observatory infrastructure. Many discoveries followed the recently expanded presence in the CCZ area, from regional faunal patterns (e.g., Amon et al., 2016; Vanreusel et al., 2016), discovery of new species (Gooday et al., 2017; Lim et al., 2017), and remarkable microbial biodiversity (Lindh et al., 2017), to a better understanding of temporal variation in seabed currents (e.g., Aleynik et al., 2017). A demonstration project, if well-integrated to ongoing studies by contractors, e.g., JPI Oceans and others, could feed data into the current EMP for the CCZ (ISA, 2012), inform all stakeholders of the environmental setting and contribute to assessing the consequences of nodule mining.

Azores Archipelago

The Azores volcanic northeast Atlantic archipelago sits above a tectonically active triple plate junction, surrounded by abyssal

TABLE 3 | Summary of possible demonstration projects, questions, advantages and assets.

Location	Key Questions	Strategic Advantages	Existing Assets
Clarion-Clipperton	Effects of seabed mining on deep-sea fauna and functions	Significant baseline data collected by industry and academics; some observations over long time periods	Industry moorings; regular baseline assessment cruises as part of industry activity
Azores Archipelago	Evaluate ocean change in relation to climate and AMOC patterns; integrated characterization of deep-sea communities and ecosystems subject to fishing and potential mining	Easy access and well positioned to link to other Atlantic observing activities	Fixed observatories at Lucky Strike and planned soon for Condor Seamount with biogeochemical sensors
Northeast Pacific	Operational data to inform hypoxia, event response, tsunamis, fisheries, and whales; The linkage of vents and seeps to each other and oceanic processes; shelf-slope exchanges; bentho-pelagic coupling	Shelf, slope, abyss, vents and seeps are instrumented; naturally occurring hypoxia altered by climate change	Many moorings and instruments are in place over regional scales at OOI and ONC
Western Pacific	Air-sea interaction in the western Pacific; comparative research between Eastern and Western Pacific circulation and heat exchange; marine weather and climate forecasts, and ensuring safety	Significant previous effort associated with a Scientific Observation Network (20 moorings)	
Ocean Trenches: Izu-Ogasawara Trench and Mariana Trench	Monitoring long-term changes in the deep-sea environment, such as warming and freshening of abyssal waters, requires data of the highest possible quality from the ocean trenches	Significant previous scientific interest; good access, existing protections	

plains with numerous seamounts, deep fracture zones, trenches, and a considerable extension of the Mid-Atlantic Ridge. It is located at the northeastern edge of the North Atlantic subtropical gyre, the Atlantic Meridional Overturning Circulation (AMOC) influences regional oceanography and Earth's climate system (Amorim et al., 2017). Prominent vulnerable marine ecosystems include deep-sea hydrothermal vents, sponge aggregations, cold water coral gardens and reefs, and extensive fields of xenophyophores (Morato et al., 2016). The Azores will host two fixed-point, well-equipped observatories, with an existing node at the Lucky Strike hydrothermal vent (Colaço et al., 2011) and another planned soon for coral gardens on the Condor seamount. These nodes will monitor the biogeochemical coupling of the benthos, water column, and atmosphere, and can provide information on ocean change in relation to climate and AMOC patterns.

Northeast Pacific: Cascadia Margin to the Juan de Fuca Ridge

The Cascadia Margin and Juan de Fuca Plate offer existing infrastructure to support significant opportunities for technologically advanced interdisciplinary ocean observation based largely on existing infrastructure. Here, the coupling of the US NSF Ocean Observatories Initiative (OOI) Cabled Array and the Ocean Networks Canada (ONC) Neptune observatory (Barnes et al., 2013; Kelley et al., 2016) provides unprecedented opportunities for regional in-depth study and decadal time–series observations of complex oceanographic processes, with a possible extension to the open-ocean Station Papa site. Collectively, the submarine cabled observatories span ocean depths from 80 to 2900 m, including approximately 1700 km of high power and high bandwidth fiber optic cables, 14 subsea terminals, and more than 30 secondary junction boxes at key experimental sites. This infrastructure provides power and communication to hundreds of seafloor instruments and state-of-the-art moorings with instrumented profilers streaming data to shore at the speed of light. The continuous, real-time, two-way communication can capture interannual and interdecadal variability, as well as document, quantify, and respond to NE Pacific transient events. The observatories also span biogeochemical and physical environments that include a continental margin strongly influenced by upwelling and expanding hypoxia (e.g., De Leo et al., 2017) and acidification (Feely et al., 2008), with widely contrasting pelagic and benthic physical and biological regimes (Barth et al., 2007; Belley et al., 2016) and host hundreds of active methane seep sites (e.g., Xu et al., 2017). A preliminary workshop in 2018 gathered NE Pacific cabled observatory operators and the wider deep-sea community to explore linking OOI and ONC demonstration project opportunities. These projects would build from existing assets by integrating observations already carried out by the cabled arrays, adding sensors and instruments to the installations and carrying out ship-based investigations during maintenance cruises.

Western Pacific

Over the last 5 years, the Institute of Oceanology, Chinese Academy of Sciences (IOCAS) has developed a Scientific Observation Network in the Western Pacific Ocean focused on a warm region of complex seafloor where variation in the deep-sea current system affects regional heat fluxes. China's Western Pacific Scientific Observation Network, established based on 20 sets of deep-sea subsurface moorings, has successfully acquired temperature, salinity, and ocean current data from the Western Pacific for three consecutive years. During the 2016 expedition, IOCAS achieved "live transmission" of deep-sea data, extending observations in 2017 to 3000 m water depth. In parallel, the ROV on the *R/V Kexue*, with a depth capability of 4500 m, mapped the seafloor including seamounts, hydrothermal vents, and cold seeps. This research has significantly advanced understanding of the structure, variability, and dynamic mechanism of three-dimensional circulation in the western Pacific, and for mass and energy exchanges between the Western Pacific Ocean and surrounding areas.

Ocean Trenches: Izu-Ogasawara Trench and Mariana Trench

Monitoring long-term changes in the deep-sea environment, such as warming and freshening of abyssal waters, requires data of the highest possible quality from the ocean trenches. Past hadal observations focused on physical parameters (Taira et al., 2005; van Haren et al., 2017), and geochemical (Gamo and Shitashima, 2018) and microbial (Nunoura et al., 2015) observations. The *R/V Kaimei*, launched in 2015, has obtained integrated observations to full ocean depths (nearly 11,000 m) using a 12,000-m-long synthetic fiber cable with conductivity-temperature-depth/dissolved oxygen sensors (CTD/O_2), water bottles, and piston or multiple corers for sampling bottom sediments. The Kaimei Trench Expedition (KATE), conducted along the Izu-Ogasawara and northern Mariana trenches in 2016/2017, sampled to 9760 m for practical salinity, absolute salinity, dissolved oxygen, carbonate system parameters, carbon and oxygen isotopes, and tracers of sedimentary organic and microbial nitrogen metabolism (Kawagucci et al., 2018). KATE data will be merged with historical hydrographic data and shared on the JAMSTEC website. Hadal KATE samples analyzed for microbial diversity and environmental metagenomics provide a basis for future integrated biological studies.

DEEP-SEA INSTRUMENTATION AND OBSERVATION TECHNOLOGY

Platform and Sensor Infrastructure

In very general terms, the essential infrastructure elements needed to support sensors and their observation include power, communications, timing, and positioning. Sometimes all of these elements may co-occur in the form of a ship or a cable node, providing large bandwidth and power. Smaller platforms (isolated mooring and surface floats) offer only a few milliwatts along a time/space trajectory, with intermittent communications and position. "Platforms" implies point infrastructure (float, mooring), whereas "observatories" implies multi-purpose, distributed and cross-platform connections, e.g., a cabled acoustic network that uses GPS to position floats and Autonomous Underwater Vehicles (AUVs), and simultaneously supports sensors such as passive acoustic monitoring, thermometry, and tomography (Duda et al., 2006; Howe et al., 2010; Mikhalevsky et al., 2015).

Historically, deep-sea data collection relied on research ships and survey vessels. Technological advances have increased their capabilities for methods such as bathymetric mapping of the deep seabed using modern multibeam echo-sounders. Devices lowered from ships can sample the water column (e.g., Rosette water samplers with CTD sensors and other sensors) and biota (various nets and trawls depending on organism size, e.g., Roe and Shale, 1979). The GO-SHIP program conducts fixed hydrographic transects every 10 years globally (Talley et al., 2016; **Figure 1**). A variety of types of corers and grabs can sample seabed sediments for geology and biology, whereas larger deep-sea organisms require epi-benthic sledges and trawls, or imaging with towed camera systems, ROVs or AUVs; the latter tools are particularly important for imaging and sampling biological communities and geological features on hard surfaces such as bedrock. A long-running effort to sample ocean temperature used XBTs deployed from research and military vessels as well as from commercial ships under the Volunteer Observing System. With the advent of Argo floats, the global, broad scale sampling by XBTs ended. The deployment of XBTs to sample temperature along repeating tracks by commercial ships has continued, mostly using T7 XBTs falling to 760 m. Some 16,000 to 20,000 XBTs are deployed annually[6].

Long-term data collection has relied on platforms such as the OceanSITES moorings that form a global network (**Figure 1**) of sensors to measure water column physical and biogeochemical parameters (e.g., sediment traps to quantify particle flux to the seabed). Bottom landers deliver sampling equipment, experiments and sensor packages to the seabed including long-term time-lapse imaging (Bett et al., 2001) and baited camera systems to observe scavenging organisms (Janssen et al., 2000), even in the deepest trenches (Jamieson et al., 2011).

Recently, permanent underwater cabled observatories have advanced fixed-point ocean observation (**Figure 1**) by enhancing their dedicated power and communication capabilities, allowing for long-term ocean and climatically important environmental observations, as well as early warning for earthquake and tsunami mitigation. Substantial innovations are expected through the use of cabled observatories for oceanography.

Over the last two decades, installation and operation of undersea cable systems for ocean observing include: the single node 4728-m deep ALOHA Cabled Observatory (ACO at Station ALOHA, the site of the Hawaii Ocean Time series); regional scale systems with multiple nodes over 100 s of kilometers represented by ONC and the United States OOI Regional Cabled Array (RCA) and DONET that also functions as a seismic/tsunami early warning system; and the S-Net system off Japan that is strictly an operational warning system (5000 km, 200 sensors). Beyond the many sensors and instruments that a broadband cabled observatory can support, some can host data-intensive technologies such as robotics, video, and *in situ* molecular measurement techniques. Observatories focused on the seafloor will offer earth and ocean scientists new opportunities to study multiple, interrelated processes over time scales from seconds to decades. These include episodic processes such as sporadic deep-ocean convection at high latitudes and submarine slides, along with their resulting biological, chemical and physical changes, as well as global and long-term changes including warming trends and ocean acidification (Favali et al., 2015).

A new effort proposes adding environmental sensors to trans-oceanic commercial telecommunications cable systems (JTF

[6]https://www.aoml.noaa.gov/phod/goos/xbtscience/faqs.php

SMART Cables[7]). Repeaters in these systems every 50–100 km (e.g., mesoscale resolving along the cable path), can provide modest power and communications[8]. Current plans call for OBP and temperature (both EOVs), with 3-component acceleration, to monitor ocean circulation and climate as well as tsunamis and earthquakes. A complete ocean, and earth, observing package generally must include seismic sensors for tsunami warnings, the study of the Earth beneath the oceans, and rapid analyses of great subduction zone earthquakes.

Manned submersibles offer directed observation and sampling (Moorhouse, 2015), targeting features of particular interest (e.g., Normark et al., 1987), to the greatest depths (e.g., Challenger Deep; Gallo et al., 2015). ROVs, and hybrid ROVs, of differing size and capability enhance such exploration. Recently, live-streaming of ROV video feeds has enabled "telepresence" of experts to enhance the value of the work undertaken at sea and share deep-sea observations widely (Bell et al., 2016). Manned submersibles and ROVs have been of great importance in expanding biological observations and sampling. Interesting developments on the ROV concept include benthic crawlers, including those hosted at deep-ocean observatories and operated via the internet (Doya et al., 2017). As opposed to benthic lander systems, these moving platforms can address spatial heterogeneity and gradients at the seafloor. As they are able to move between observations, they also allow for semi or non-destructive measurements (e.g., of seafloor respiration with benthic chambers; Smith et al., 2014) or, once the technique is available, time series sampling of material from the seafloor (Brandt et al., 2016). Ideally, crawlers are connected to underwater nodes of submarine cables (e.g., Purser et al., 2013) but there are also crawlers that allow for autonomous operation in other regions of the open ocean.

Recent rapid technological advances have increased the diversity of ocean observation, driven by a need for greater spatial and temporal data collection and improved efficiency. Most notably, autonomous technology has expanded the increased capability of oceanographic research ships, and vessel-launched sensors. For example, the autonomous network of around 3500 Lagrangian Argo floats, now deployed throughout the global ocean, report temperature and salinity profiles from the upper 2000 m (Gould, 2005; **Figure 1**). Recently developed "Deep Argo" floats expand the parameters measured and depth range to 6000 m, while the BCG Argo initiative seeks to extend observation capacities of autonomous profiling floats to include biogeochemical and biological variables.

Marine Autonomous Systems (MAS) for ocean observing include static, fixed-point observatories (Cristini et al., 2016), and a variety of mobile platforms. Collectively, these systems extend oceanographic observations to broader spatial and temporal scales (Rudnick et al., 2004; Hartman et al., 2012) in oceanography (Rudnick et al., 2004), marine geoscience (Wynn et al., 2014), habitat mapping (Robert et al., 2016), and benthic ecology (Morris et al., 2014) for both science and industry (Wynn et al., 2014). Though cost-effective for long-term and large-scale monitoring programs, comparing autonomous data with traditional approaches remains a key challenge (Bean et al., 2017).

Like Argo floats, "submarine gliders" are slow-moving, AUVs capable of long deployments in the water column (months in duration). They can cross ocean basins (Glenn et al., 2011) profiling the water column in a "saw-tooth" pattern for a wide range of parameters (Suberg et al., 2014) that continue to expand as manufacturers develop and miniaturize new sensors. Gliders relay data in near-real-time via satellite communication. As with floats, these characteristics favor collection of water column data at long temporal and spatial scales, but their slow speed confounds spatial and temporal variability. Wave gliders have recently become available as an alternative autonomously moving platform that can be used in the open ocean. Wave motion is used for moving the vehicles and also provides the energy necessary for measurements, operation control, and communication. Staying on the ocean surface they cannot host sensors for deep ocean observation but may serve as communication hubs exchanging data acoustically with deep-sea installations in the area (e.g., moorings and landers) and connecting them to satellite data transmission. This allows for near-real-time data accessibility from remote locations and for sending commands to deep-sea platforms for adaptive observations.

Propeller-driven AUVs include systems differing in levels of autonomy, navigation, endurance and payload, for high precision systems for seafloor mapping purposes (multibeam echosounder, side-scan sonar, sub-bottom profilers) as well as seafloor imaging of geological and biological features and water column data collection. Lack of endurance and need for service constrain AUVs, pointing to needs for underwater docking stations for power and communications, likely supported by cable systems.

Collaborative research networks maximize effectiveness of observing systems. For example, ONC's large ocean observatory network delivers a wide variety of inter-related science services and data products including geo-hazard, oceanographic data, ecosystems and policy support (Heesemann et al., 2014). In Europe, the European Multidisciplinary Seafloor and water column Observatory (EMSO) is working to coordinate ocean data service (Favali and Beranzoli, 2009). In many ways, this synthesis aims to provide a vision for the global network, including deeper observation needs that will contribute to GOOS in the coming decades.

Sensors and Emerging Technologies

Instrument deployments in the deep ocean face challenges of accuracy, longevity, pressure resistance, power, communications and timing, miniaturization, drift correction, and deployment costs. Relative to ships, cost savings in orders of magnitude can be achieved by mounting sensors on cabled, autonomous, and robotic submersibles.

Seismic and acoustic sensor technologies matured decades ago, and research vessels now routinely deploy digital ocean bottom seismometers and hydrophones (OBS/H) both in a campaign mode and connected to real-time cabled observatories. Advanced seafloor emplacement methods include both buried

[7] http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

[8] https://eos.org/meeting-reports/submarine-cable-systems-for-future-societal-needs

and borehole systems to use these sensors to resolve the physical structure of the seafloor, lithosphere, and 3D tomography of the planet, as well as the propagation of acoustic and seismo-acoustic signals within the seafloor and in the water column. In addition to their scientific prowess, and in concert with pressure sensors, real-time seismic systems have a crucial societal role for tsunami warnings. Intriguingly emerging sensing technology shows the potential use of optical fibers (perhaps within telecommunication cables) as acousto/seismic and temperature sensors (Lindsey et al., 2017; Marra et al., 2018).

Sensors that measure physical variables in the deep-ocean such as temperature, salinity, and velocity on ships, moorings, and cabled observatories are relatively mature. Ongoing testing of miniaturized versions that reduce power requirements and drift offer promising application in deep floats and gliders and animal-borne tags. Instrumentation of marine animals with a variety of sensors that not only report on animal movement in four dimensions (horizontal, vertical and time) but on the environment animals are moving within, give insights into how physical and chemical ocean properties shape animal communities and behaviors (Hussey et al., 2015). "Animal oceanographers" have collected vast amounts of CTD data in remote areas often inaccessible to other sensor platforms and are enhancing regional ocean models (e.g., polar regions; Treasure et al., 2017; Silvano et al., 2018). Several groups are globally aiming for standardized quality control, metadata, and data sharing of these products (Roquet et al., 2017). Additional sensors and improvements of animal-borne tags are continuously developed, such as active and passive acoustics or imaging (Thomson and Heithaus, 2014; Fregosi et al., 2016), and miniaturization as well as tag attachment (Shaikh et al., 2019). Already these efforts are becoming valuable for conservation policy and management decisions (Hays et al., 2019) and will prove particularly useful in deep-sea environments.

On a smaller scale, scientists need better and ubiquitous sampling of mixing and turbulence as well as easier and more widespread measurement of heat flux between the ocean and the sea floor. Satellite measurements of sea surface height are mature, while gravity/bottom pressure are less so. Both are essential for global coverage and currently lack high temporal and spatial resolution. A new method for routine *in situ* calibration (better than 1 mm/year; Wilcock et al., 2018) promises transformative improvement in measurement of OBP that will greatly facilitate the separation of mass and steric/heat content effects on sea level (Ponte, 2012). Recent work demonstrates the importance of OBP measurements in resolving meridional overturning circulation transport, and the possibility of optical clocks that sense changes in gravity (Hughes et al., 2018). As mentioned in Section " Ocean Bottom Pressure," OBP is in process to become an EOV.

Long-range acoustic "GPS" carried out by an underwater-array of acoustic transducers can provide accurate, long-term, high temporal resolution float tracking (velocity EOV), long-range AUV/glider navigation (including under ice), and acoustic tomography (temperature EOV) if the platforms are equipped with acoustic receivers. The same acoustic receivers can carry out wind and rain measurements and monitor marine mammals and "soundscapes" (ocean sound EOV). Cabled (ATOC) and moored scenarios have used this mature technology for decades, with no significant impact on marine mammals. The high signal to noise ratio, no calibration, quadratic growth in data with number of instruments, and sampling at the speed of sound collectively enable high accuracy and high temporal resolution of basin-scale heat content.

In contrast to routine ship- and cable-based deployment, observations of inorganic carbon via alkalinity, pCO_2, and pH on autonomous platforms are currently in the concept or pilot phase. The analytical methods for inorganic carbon are well developed along with certified reference materials, (for DIC and TA) to meet long-term accuracy requirements (Dickson et al., 2007; Wang et al., 2007). Better-calibrated measurements of carbonate variables on autonomous platforms are in development, which will be useful to monitor short-term variability and seasonality. However, they will likely not be accurate enough to monitor decadal variation, so the accuracy of inorganic nutrient measurements requires improvement in order to quantify changes in the deep ocean. Sensors mounted either on a CTD package or on autonomous vehicles can measure oxygen precisely. One key advance has been the ability to reference oxygen sensors to air, reconfiguring profiling floats and gliders to a standard whenever the sensor is at the surface (Bushinsky et al., 2016). Profiling optical tools (e.g., chl-a fluorescence, optical backscatter, holography, and light-field imaging) can determine particle type-and size-distributions in time or space (e.g., Briggs et al., 2011), allowing quantitative inferences on particulate organic Remineralization Length Scale (RLS; Buesseler and Boyd, 2009), or the types and sizes of particles associated with variation in RLS.

Numerous emerging sensors and methodologies support observations of deep-ocean particle and remineralization processes. Increasingly reliable particle traps that quantify vertical particle flux can also add imaging systems to assess particle sizes and *in situ* settling velocities or be deployed with neutrally buoyant drifting platforms. Biological oxygen demand or remineralization rate observation techniques are quickly maturing for use across platforms; these are needed to assess the fate of organic matter at the seafloor (seafloor respiration is a suggested EOV). Oxygen consumption measurements no longer require on-board bottle and core incubations but can be assessed *in situ* by chamber incubations or by micro-profiler recordings of porewater oxygen distributions (e.g., Glud, 2008). Additionally, eddy covariance measurements, an emerging, non-destructive method, has been used successfully in a range of environments including the deep sea (e.g., Berg et al., 2009). All *in situ* oxygen consumption measurements benefit from the implementation of optical measurements with oxygen optodes (Klimant et al., 1995) that show low drift and stirring sensitivity and are now commercially available in many different sizes and configurations. Trophic structure of food webs requires assessing standing stock or biomass distribution across taxa and faunal size classes. Some taxa and productivity can be assessed through the monitoring of bio-optical instrumentation, bioluminescence or by sound collected via passive or active hydro-acoustic measurements (ocean sound is in the process of becoming an EOV). Stereoscopic imaging, holography, and light-field cameras show promise for quantifying fragile marine snow particles and important ecological quantities such as gelatinous zooplankton.

The study of natural, stable carbon, nitrogen, and sulfur isotope signatures (including compound-specific analyses), isotopic enrichment experiments, lipid biomarkers, gut content analyses, and the accumulation of pollutants or tracers found in harvested species or those captured in traps can document trophic interactions and food-web structure. Adaptation and tolerance to ecosystem change are commonly assessed through *in situ*, shipboard or laboratory experiments, however, logistical challenges limit this approach.

Challenges associated with observation and sampling limit diversity baseline and impact studies. Diversity indicators, such as rare versus abundant species, can help in estimating relative abundances of organisms, resilience to change, and recovery of impacted communities. Further research could identify indicator species that reflect the status and health of different ecosystems and provide early warning of impending change. Automated plankton samplers that collect material for later analyses are being developed and used, e.g., with towed and moored instruments and shipboard underway sampling systems (e.g., Metfies et al., 2016; McQuillan and Robidart, 2017).

Genomics (Multi-Omics)

High-throughput technologies such as DNA sequencing and mass-spectrometry are revolutionizing ecology and environmental management studies. A very promising approach is the analysis of eDNA that biota release into the environment and that allows for observations of biodiversity without the need to sample the organisms themselves. However, successful application depends on baseline knowledge of species identity, and in the case of eDNA, requires information on local versus exogenous sources and longevity of the DNA signal in the environment. Combinations of metabarcoding, metagenomics, metatranscriptomics, metaproteomics, metabolomics, or epigenomics allow the holistic description of any biomolecular environment, as shown for marine plankton (Lima-Mendez et al., 2015), coastal benthos (Beale et al., 2017), single cells (Lan et al., 2017) or host-symbiont models (Liu et al., 2012; Clark et al., 2017). Current applications of omics-related approaches to deep-sea environments focus mainly on diversity surveys of prokaryotes (e.g., Nunoura et al., 2018), microbial eukaryotes (Pawlowski et al., 2011; Lejzerowicz et al., 2014) and metazoan communities (Sinniger et al., 2016). Multi-omics have also been used to monitor resilience to pollution (e.g., Deepwater Horizon oil spill; Mason et al., 2012; Kimes et al., 2013; Smith et al., 2015), but a lack of reference data impedes broader applications to deep-sea organismal and community functional diversity and ecological interactions. Because deep-sea sediments harbor abundant extracellular DNA (Dell'Anno and Danovaro, 2005), one out of two sequenced DNA molecules might belong to long-dead organisms (Corinaldesi et al., 2018). Given that extracellular or inactive cell population DNA might saturate high-throughput sequencing data, basic omics approaches such as metabarcoding and metagenomics may provide only fragmentary information about active populations. Moreover, several hours to transport biological material from abyssal depths to the surface will certainly affect organisms and bias interpretation. Specifically tailored equipment able to retrieve undisturbed metatranscriptomic samples has quantified *in situ* metabolism of hydrothermal vent species (Sanders et al., 2013). A Deep-water Environmental Sensor Processor (D-ESP) was successfully deployed for *in situ* qPCR detection of methanotrophic bacterial species (Ussler et al., 2013), and a recent study improved extraction of nucleic acids from deep-sea settings (Muto et al., 2017). Other innovative instruments including microfluidic systems (Macaulay et al., 2017) could enable multi-omics analyses of deep-sea marine microbe cells (Robidart et al., 2012). The deep ocean could benefit from a large-scale metabarcoding, metagenomic, and transcriptomic census, as has been conducted for marine plankton (Keeling et al., 2014; Carradec et al., 2018). However, researchers must couple accumulation of omics data with other observation and cultivation data (Vilanova and Porcar, 2016) in order to reconstruct ecological systems and better understand deep-sea biology.

Imaging Techniques

The utility of optical imaging continues to grow (e.g., Durden et al., 2016; Morris et al., 2016; Ramondenc et al., 2016; Thornton et al., 2016). Commercially available systems can now image objects from tens of μm to cm and larger, e.g., with holographic or structured light systems (Davies et al., 2015). However, technologies for *in situ* plankton imaging, e.g., Lightframe On-sight Key species Investigation (LOKI, Schulz et al., 2010), flow cytometry, and automated species recognition technology require further work to enhance biodiversity assessment. Indeed, the mosaicing of video and image data now occurs continuously from m to km scales at landscape and policy-relevant scales. Many platforms support imaging tools with great promise in being able to mount imaging systems to long range and long endurance AUVs that can navigate repeat vertical sections and seafloor surveys of hundreds of km and hectares.

Without a seafloor background to scale against, sizing objects in the water column remains challenging. Georeferenced images, structured light, stereoscopic imaging, holography, light-field, and flow cytometry cameras show great utility for quantifying habitats, geologic resources, fragile marine snow particles and important ecological quantities from gelatinous zooplankton to fish (e.g., Wynn et al., 2014; Aguzzi et al., 2015; Ramondenc et al., 2016; Peukert et al., 2018). On the seafloor, imaging can now readily quantify individuals approximately 1 cm in size, patches of individuals, how they relate to habitat features, and how they relate to landscape features (e.g., Morris et al., 2016; Thornton et al., 2016). Camera systems readily adapt to deep-sea deployment with appropriate window and housing depth ratings. Processing techniques can also render images into 3D data with known photogrammetric error (Kwasnitschka et al., 2016; Thornton et al., 2016). Supporting navigation and camera position and geometry data including structured light, acoustic imaging, or taking advantage of light field (i.e., plenoptic) or stereo-image data processing collectively enable this approach. The improvements from imaging type and photogrammetric approaches allows investigators to extract particle biology and ecosystem EOV data from images in a way that begins to approach the accuracy and precision of physics and biogeochemistry EOVs. Imaging technology includes the advantage of imaging many orders of magnitude more objects than can be sampled otherwise and with little or no disturbance, such as to fragile marine snow particles. However, image data typically require context information such as a regional image guide or catalog of species, or calibrations of size, weight, and/or biogeochemical composition. As with omics, optical and acoustic imaging data severely tax data systems.

Super-Deep Hydrographic Measurements

Shipboard hydrographic measurements conducted at hadal depths for climate studies require the highest possible quality measurements because of the low signal-to-noise ratio. In the past, water sampling in ocean trenches used bottles equipped with reversing thermometers, or CTD observations obtained without water samples to correct the CTD data. Today, full–ocean–depth (11,000 m) reference quality measurements are possible with modern conductivity-temperature-depth/oxygen (CTD/O_2) sensors and water sampling equipment through the use of synthetic (polyarylate) fiber coaxial cable (Kawagucci et al., 2018). Acquiring data of the highest possible quality requires *in situ* calibration of CTD/O_2 sensors. A deep-ocean standard thermometer realizes SI traceable measurements with an uncertainty of 0.7 mK after correction for pressure (Uchida et al., 2015). Practical salinity and dissolved oxygen data require water samples to calibrate sensors *in situ*. In the Mariana Trench, for example, a salinity profile obtained with *in situ* calibration is reasonably homogeneous (unpublished data, D. Yanagimoto personal communication), whereas without calibration salinity artifactually increases in the bottom layer. Previous comparisons report a similar artifact (Taira et al., 2005; van Haren et al., 2017).

Rotation and related motion of the CTD package on its cable also affect CTD data quality (Uchida et al., 2015). Used together, an underwater slip-ring swivel, a stabilizing fin, and a traction winch to compensate for the ship's motion enable efficient and safe acquisition of high-quality CTD data (Uchida et al., 2018), although pressure hysteresis of the CTD sensors (temperature, conductivity, and oxygen) must be considered. However, even the highest quality salinity measurements are not adequate for climate studies in ocean trenches. For example, long-term salinity changes in the North Pacific deep ocean due to temperature changes of $\sim$0.0001 per decade are expected from the temperature-salinity relationship, whereas CTD salinity measurements resolve 0.0004 (0.002 for a laboratory salinometer). Ambiguity of the certified salinity value ($\pm$0.001) of standard seawater used to calibrate laboratory salinometers adds another problem (Kawano et al., 2006). An optical interferometric salinometer currently in development uses high-precision refractive index measurements to resolve absolute salinity to better than 0.0002. However, even the state-of-the-art optical interferometric salinometer must be calibrated against standard seawater, which itself requires certification of absolute salinity so that it can be used as reference material for absolute salinity measurements (Uchida et al., 2011).

DATA DISCOVERY, STANDARDIZATION, INTEROPERABILITY, AND SYNTHESIS

Addressing the ambitious deep-sea science and management challenges described above will require an unprecedented level of data accessibility and integration. The difficult and expensive nature of deep observation means that data will remain sparse, and sharing even more critical.

Current Status and Challenges

Results from the Inventory of Deep Ocean Observing (see Section "Status of Deep-Ocean Observing") indicate that in many cases the data being collected by deep-ocean observatories are being preserved and made freely accessible online to the larger community. Where exceptions exist, they are largely in smaller programs that lack long-term funding and informatics expertise, in one-time sampling projects, or of less mature EOVs where methods are still evolving.

Despite widespread deep-ocean data availability, challenges remain. Though efforts toward standardization continue, users are often working with heterogeneous systems, varied data formats and access methods, and varied or insufficient metadata. From large observatories to individual labs, there are multiple cyberinfrastructure approaches in operation and in development which work to support data acquisition, storage, processing, and visualization in a single, distributed system. These range from simple data servers containing .csv files, to ERDDAP-based systems[9] with a stable, versioned file structure such as the ones used by the NOAA IOOS[10], to compute-on-demand systems like the one used by the OOI[11].

Further, anyone familiar with attempting to locate or convert data records that exist only in a large collection of mysterious floppy disks or tape reels is well aware of the problem of changing data storage and data delivery technology. The era of "big data" has only accelerated this issue, as more different types of data are collected, and large-volume data types such as video are increasing, that require long-term storage in a stable and accessible format. Future efforts should go into processing of data on cloud servers, using open-source software packages to enable interactive and collaborative data discovery, exploration, and manipulation (e.g., Pangeo[12] for big data geosciences research[13]), but best practices are yet to be widely developed and shared for using cloud resources. Finally, discovery of accessible resources is a substantial challenge. Deep data are served by a complex patchwork of project-specific websites, institutional collections, national and international data centers, thematic data repositories, and journal data appendices. Searching for data from a particular EOV measurement or region requires searches in many systems, not all of which are known to inexpert users. The same or similar data are often served

[9]https://coastwatch.pfeg.noaa.gov/erddap/index.html
[10]https://ioos.noaa.gov/
[11]http://oceanobservatories.org/
[12]http://pangeo.io/
[13]http://pangeo-data.org/

from multiple source repositories, with unclear provenance to disambiguate the versions.

Future Steps

To achieve a future where deep observations are fully shared and able to support broad science and societal needs requires several components: wide agreement on the need to share data, standards to achieve consistency and comparability across data sources, better registries and cross-repository search tools to improve discoverability, and capacity building for both observatories capturing data and those using the data.

Open Data Policies

The critical foundation in building an ecosystem of accessible and usable deep-sea data is agreement among scientists, funding agencies, publishers, governments, and NGOs that deep ocean data should be openly and freely shared. The FAIR guiding principles (Wilkinson et al., 2016) provide a set of widely endorsed practices to ensure that data, tools, and other cyberinfrastructure are Findable, Accessible, Interoperable and Reusable. It does not require specific technologies, as technology will evolve over time, but rather identifies specific characteristics to meet, such as implementing persistent identifiers for all data, having both human-readable and machine-actionable metadata, and having well-described protocols for both humans and machines to access the data.

While FAIR is gaining support globally[14], and has been endorsed by both the GOOS and DOOS communities, other similar and well-crafted position and policy statements exist. What is important is not which statement is endorsed, but that the observing community widely adopts a philosophy of data stewardship that ensures data are secure, widely available, and documented for usability. As stated by the American Geophysical Union (2015) "Earth and space sciences data are a world heritage."

Standards

In order for data systems to work together today, and continue to work in the future, there must be community acceptance of standardized rules for complete, consistent metadata (e.g., Climate and Forecast (CF), International Standards Organization (ISO), or Federal Geographic Data Committee (FGDC) standards) and the use of self-describing data formats (e.g., NetCDF) to allow synthesis of different types of data into a single archive. Archiving in national databases (e.g., AODN[15]) allows for both long-term storage and accessibility, but there is a pressing need for standardized metrics, implementation of common nomenclature within and across fields, improved provenance tracking, and the application of real-time quality control. Some fields and sub-fields have settled on one or two standards (e.g., IRIS, GenBank, WoRMS, OBIS, etc.), but they are not all interoperable, and the nomenclature varies widely. Concerted coordination, and support for the communications platforms needed to reach consensus, are necessary.

Registries and Coordinated Discovery

To reduce the challenges of finding deep-ocean data, particularly to non-experts, a concerted effort is needed by the deep observatory community to converge on a small number of widely used registries for data discovery, and to support standards and APIs to allow searches in a central location to query across multiple repositories. Efforts such as GEOSS Portal[16] and EMODnet[17] show the promise of this approach.

To bring all ocean data toward FAIR standards will require substantial capacity development involving all stakeholders. Capacity building training programs related to ocean observing already exist and could offer opportunities to build deep ocean-dedicated-training under these umbrellas. (see Section "Capacity Building" below).

MOVING FORWARD

Value Propositions

Oceans provide goods and services that are imperative to human survival and well-being. The ocean's "Blue Economy" is one of the richest and fastest-growing economies, projected to reach over USD 3 trillion by 2030, doubling its current value (OECD, 2016). However, climate change and potentially destructive and unsustainable exploitation of ocean resources put the world's Blue Economy at risk. To ensure that the oceans and Blue Economy are managed efficiently, sustainably, and equitably, it is critical to develop ocean observing programs to improve understanding of the oceans and how they are changing. Key elements of future observing efforts will be community engagement, capacity building and data management.

Ocean observing offers benefits to all elements of the Blue Economy. For example, ocean observations using ROV data have been used to understand the effects of prevailing environmental conditions (current velocity, biofouling) on oil and gas extraction activities, ultimately leading to better asset (infrastructure) management and concomitant cost-savings (Macreadie et al., 2018). Ocean observation, openly and easily accessible (see Section "Data Discovery, Standardization, Interoperability, and Synthesis") can enhance environmental and social responsibility and improve EIA effectiveness and efficiency (Vardaro et al., 2013; Eide and Westad, 2018), which may lead directly to increased regulator and societal confidence and add to the credibility of blue industries (**Box 3**).

Community Engagement

Developing a strategy for deep-ocean observation requires attracting more students, early career scientists, and the general public in related science and technology fields. This can be achieved by engaging them with deep-sea research challenges, raising awareness of deep-sea exploration and discoveries, and emphasizing the need to fill gaps in ocean/climate interaction processes, seafloor geological processes, and deep-ecosystem functions and dynamics. Citizen science has proven valuable

[14]http://www.copdess.org/enabling-fair-data-project/enabling-fair-project-overview/

[15]http://imos.org.au/facilities/aodn/

[16]http://www.geoportal.org/

[17]http://www.emodnet.eu/

for annotations of deep sea-imagery. Live broadcasting of scientific missions, known as telepresence, (e.g., ROV dives) or imagery and sound recordings from cabled observatories (e.g., Neptune Canada[18]) have provided unprecedented public access and engagement. There is a need to identify new engagement opportunities in data management, technology innovation, and transfer of best practices, emphasizing broad disciplinary scope and interdisciplinary science. Production of education materials (books, factsheets, tutorials, e-learning, and museum installations) can help disseminate scientific advances to scholars and students. Development of outreach events and ocean literacy material can attract the attention of school children and local communities and emphasize the importance of the deep-ocean contribution to the prosperity and well-being of humanity.

Capacity Building

Existing capacity building training programs related to ocean observing can offer opportunities to contribute or build a dedicated deep-ocean training program under these umbrellas and can contribute to data coordination. UNESCO/IOC IODE and WMO Learn Education and Training Programme[19] (ETRP) continue to make efforts that facilitate access to a wide range of training materials. The OceanTeacher Global Academy[20] initiative allows training courses to take place simultaneously in multiple locations through the use of video conferencing technology.

The Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) from UNESCO and IOC has Capacity Development plans to empower developing States [Least Developed Countries (LDCs) and Small Island Developing States (SIDS)] by providing expert training on the applications of ocean observation data for understanding and predicting regional weather, ocean, and climate. The Partnership for Observation of the Global Oceans (POGO) acts as a forum for leaders of major oceanographic institutions to promote global oceanography, particularly for the implementation of international and integrated GOOSs, and provides training and technology transfer to emerging economies to build awareness of future challenges[21]. Additional training opportunities are offered by the GEO, Integrated Marine Biosphere Research (IMBeR), International Ocean Colour Coordinating Group, and North Pacific Marine Science Organization. Also "summer schools" or training workshops are organized by deep-ocean scientific networks such as INDEEP, DOSI, IODP, and InterRidge.

In addition to dedicated courses, there is a need to more widely disseminate availability of berth spaces at sea and training internships on field research, instrumentation development, and data analysis of relevance to deep-sea observation. Funding support for early career scientists and qualified technical personnel from developing countries can be requested from the POGO-SCOR Visiting Fellowships program[22], and the ISA

[18] http://www.oceannetworks.ca/sights-sounds/live-video

[19] http://learn.wmo.int

[20] http://www.oceanteacher.org

[21] http://www.ocean-partners.org/training-education

[22] http://ocean-partners.org/pogo-scor-fellowship

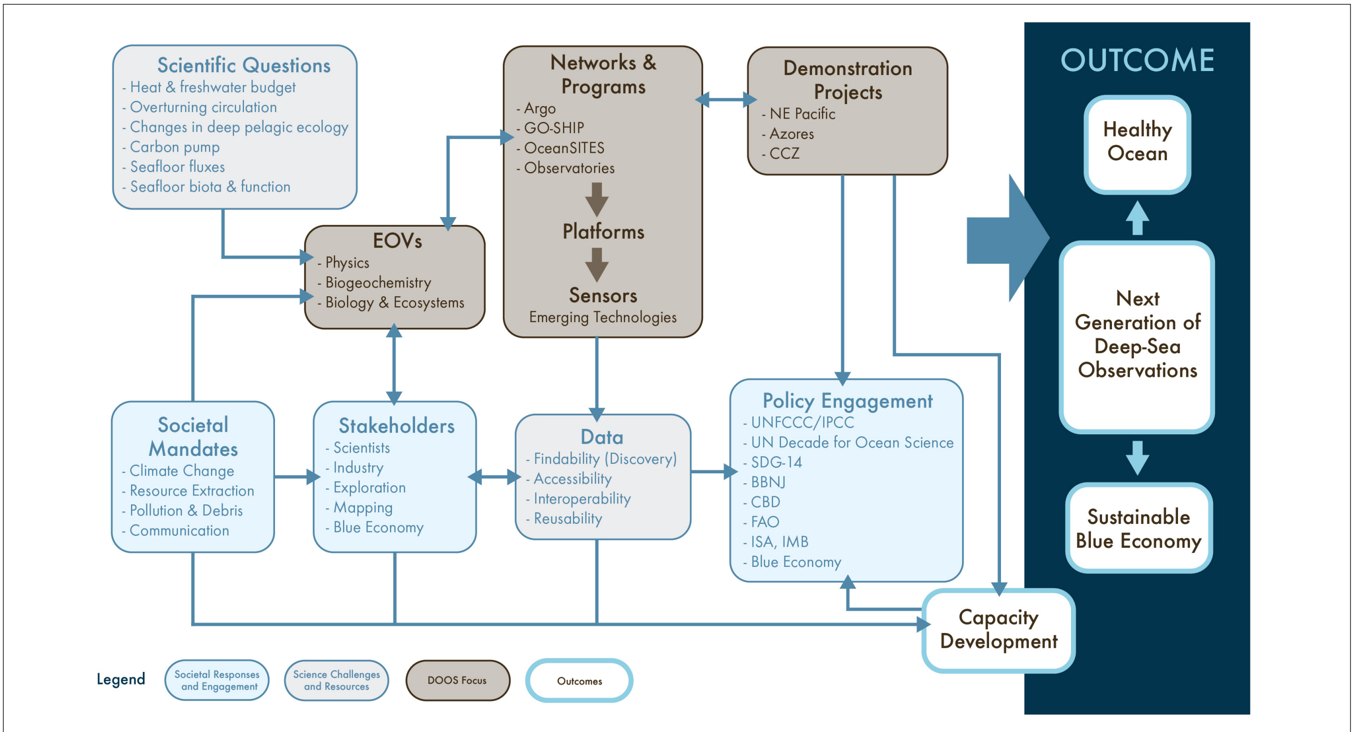

FIGURE 5 | The key components of a deep-ocean observing strategy designed to promote healthy oceans and a sustainable blue economy.

Endowment Fund for the InterRidge Student and Postdoctoral Fellowship Program for collaborative marine scientific research. Substantial interdisciplinary efforts to develop new capacity to monitor deep-sea environments and biodiversity are required, including the sharing of skills and best practices for the use of existing instrumentation (e.g., robotics, sensors) and for the development of new equipment.

Summary and Recommendations

A DOOS is conceptualized in **Figure 5** and is put forward in the following recommendations.

1. Agree upon a set of EOVs that will capture current baseline conditions and future changes in the deep ocean, its ecosystems, and the services they provide. Work with GOOS Expert Panels and the scientific community to standardize, mature and operationalize these EOVs, and advance the availability, reliability, and longevity of autonomous systems (sensors and platforms) that can make these measurements. Emphasize approaches that may be scaled up to provide near-global coverage.
2. Develop a means to identify new deep-ocean data needed to address key scientific and societal needs. Develop new communication tools to inform the science community and convey deep-ocean observing needs and advances across disciplines, regions, sectors and jurisdictions. One thoughtful suggestion is to consider conducting a large-scale, decadal metabarcoding, metagenomic, and transcriptomic census in the deep ocean, as has been conducted for marine plankton (Keeling et al., 2014; Carradec et al., 2018).
3. Expand the deep-ocean observing capabilities and capacity (a) by engaging corporate citizens (e.g., the energy, fisheries, seabed mining, cable and shipping industries), the ocean exploration community, biodiversity interests and the public; (b) through enhanced vessel servicing activities; and (c) by reusing and repurposing existing data products. Develop approaches to incentivize engagement by a broader range of stakeholders to achieve this.
4. Enhance data FAIR for scientists and non-experts by converging on a small number of widely used registries for data discovery, and support standards and APIs to allow searches in a central location to query across multiple repositories.
5. Work to integrate deep-ocean observing across disciplines, share skills and best practices for the use of existing instrumentation (e.g., robotics, sensors) and for the development of new equipment (e.g., through demonstration projects).
6. Create collaborations across the deep components of existing regional observing networks such as those in the MBON, OOI, ONC, EMSO 2020, AtlantOS, SOOS, and FRAM and integrate these with global programs (e.g., ARGO, deep ARGO, BGC Argo, OceanSITES, GO-SHIP).
7. Build deep-ocean observing capacity by expanding existing training programs to build "deep-ocean" dedicated training under these umbrellas, while simultaneously integrating capacity building seamlessly into existing and future observing programs.
8. Facilitate use of deep-observing data by a broad range of stakeholders, particularly in the economic and international policy sectors, to achieve a healthy ocean and sustainable blue economy.
9. Engage with the modeling community to (a) better understand and respond to requirements for verification, validation, and calibration of models used for prediction; and (b) improve inverse modeling approaches for optimally extracting and combining information contained in theoretical foundations, where available (e.g., equations of motions), and sparsely sampled observations.

AUTHOR CONTRIBUTIONS

LL, BB, AG, PH, BH, FJ, AM, HR, PS, and KS helped to conceive the manuscript, coordinated author contributions, wrote the text, edited and contributed to the figures and tables. DB, SB-P, CB, MB, DJB, MC-S, AC, ME, AF, KG, DJ, KK, DK, NLB, AL, FL, PM, DM, FM, TM, AN, JP, CS, SS, HU, MV, RV, and RW contributed the manuscript ideas and text.

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frontiers in Marine Science

REVIEW
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Evolving and Sustaining Ocean Best Practices and Standards for the Next Decade

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The oceans play a key role in global issues such as climate change, food security, and human health. Given their vast dimensions and internal complexity, efficient monitoring and predicting of the planet's ocean must be a collaborative effort of both regional and global scale. A first and foremost requirement for such collaborative ocean observing is the need to follow well-defined and reproducible methods across activities: from strategies for structuring observing systems, sensor deployment and usage, and the generation of data and information products, to ethical and governance aspects when executing ocean observing. To meet the urgent, planet-wide challenges we face, methods across all aspects of ocean observing should be broadly adopted by the ocean community and, where appropriate, should evolve into "Ocean Best Practices." While many groups have created best practices, they are scattered across the Web or buried in local repositories and many have yet to be digitized. To reduce this fragmentation, we introduce a new open access, permanent, digital repository of best practices documentation (oceanbestpractices.org) that is part of the Ocean Best Practices System (OBPS). The new OBPS provides an opportunity space for the centralized and coordinated improvement of ocean observing methods. The OBPS repository employs user-friendly software to significantly improve discovery and access to methods. The software includes advanced semantic technologies for search capabilities to enhance repository operations. In addition to the repository, the OBPS also includes a peer reviewed journal research topic, a forum for community discussion and a training activity for use of best practices. Together, these components serve to realize a core objective of the OBPS, which is to enable the ocean community to create superior methods for every activity in ocean observing from research to operations to applications that are agreed upon and broadly adopted across communities. Using selected ocean observing examples, we show how the OBPS supports this objective. This paper lays out a future vision of ocean best practices and how OBPS will contribute to improving ocean observing in the decade to come.

Keywords: best practices, sustainability, interoperability, digital repository, peer review, ocean observing, ontologies, methodologies

INTRODUCTION

The Ocean Observing Challenge

The oceans play a key role in global issues such as climate change, food security, sustainable consumption and production and human health. The oceans are enormous, transcending human-defined ocean boundaries, and they are continuous and uninterrupted in time and space. The well-being of humanity is tightly linked to the oceans and the seas as repeatedly stated in multiple policy frameworks including the United Nations (UN) Sustainable Development Goals (SDG) (Wackernagel et al., 2017; UNSDG, 2018) and the European Union's (EU's) Marine Strategy Framework Directive[1].

The vast dimensions and internal complexity of the oceans and the seas make observing and monitoring challenging, particularly in remote and hostile environments. Therefore, observing activities require careful structuring for improving their efficiency, coherence, and coverage. Ocean observing experts have long recognized these challenges (Olson, 1988; Kulkarni, 2015) as well as the need to address them transnationally. A first and foremost requirement for collaboration in ocean observing is the need to follow well-defined methods. In this paper, "Ocean Best Practices" include all aspects of ocean observing from research to operations to products that benefit from proper and agreed upon documented methods. Ocean best practices are an essential component of the growing operational oceanographic services that provide ocean forecasts at multiple time and space scales.

In a generic sense, "ocean observing" can be summarized by a chain of processes addressing "why to observe?" (requirement setting process), "what to observe?" (scoping of observational foci), "how to observe?" (coordination of observing elements), and "how to integrate, use and disseminate observational outcomes and understand their impacts?" (data management, analyses and creation and assessment of information products). This chain may be executed for a single scientific project that aims to formulate or refine a hypothesis, or by an environmental agency delivering operational products (e.g.,

[1] www.msfd.eu

warning the public about a hazardous event). These aspects make clear that "ocean observing" is more than just taking observations. Only by considering a need for observing and by making sure that information (including observations) can be merged into a product/outcome is the act of ocean observing complete and meaningful.

Motivated by the 2009 OceanObs'09 conference[2] in Venice, Italy, the "Framework of Ocean Observing" (FOO) (Lindstrom et al., 2012) was documented as a structural approach for maintaining a sustained Global Ocean Observing System (GOOS). The FOO introduces two important concepts: (1) a system engineering approach to ocean observing; and (2) Essential Ocean Variables (EOVs). For the first, the result has been an increased awareness of the observing system value chain and the importance of the operating sequence of processes from societal and scientific requirements via observations to end-user products (see **Figure 1**). A value chain, which is a term adopted from economics, is broadly defined as a set of value-adding activities that one or more communities perform in creating and distributing goods and services (Longhorn and Blakemore, 2008). Evaluating the value chain for a system reveals not only its structure, but allows identifying and optimizing the processes operating within the system (Porter, 1985). For the second concept, the EOVs (GOOS, 2018)[3], following the Essential Climate Variables model (Bojinski et al., 2014), were introduced in the FOO to prioritize parameters to observe, based on feasibility and societal and science impact. The feasibility is gauged, in part, by the observing system's component maturity levels (called Technology Readiness Levels (TRL) and discussed in section "Approaches to Meet OBPS Requirements"). The "societal impacts" analyzed in the FOO ultimately take into account the legal and social dimensions of ocean observing (see, for example, Miloslavich et al., 2018a). This includes the challenges of cooperation, trust, ethics and others that also must be addressed if the ocean information chain is to be effective for society (Barber, 1987).

Introduction to Best Practices and Standards

Best practices and standards are the two most common dimensions present in broadly accepted methodologies and serve to ensure consistency in achieving a superior product or end state. As many readers may not be familiar with standards and their formation nor have direct experience with best practices, a short introduction is included here. Best practices and standards are part of a continuum of community agreements (Pulsifer et al., 2019). Best practices, in the way the term is used in this paper, are descriptions of methods, generally originated bottom-up by individual organizations. Best practices can become standards if established by panels in standards organizations or equivalent. This section will look at both standards and best practices, focusing first on best practices.

A best practice is a methodology that has repeatedly produced superior results relative to other methodologies with the same objective; to be fully elevated to a best practice, a promising method will have been adopted and employed by multiple organizations (Simpson et al., 2018). This definition is similar to definitions used in other fields for best practices (Bretschneider et al., 2005). Best practices can come in many forms such as "standard operating procedures," manuals or guides. However, they all have a common goal of improving the quality and consistency of processes, measurements, data and applications through agreed practices.

The diversity within our ocean community, and the continuous and asynchronous evolution of technology and capacity means that there can be several "best" approaches actively used that have not been universally evaluated across the observing community (see section "The Issues for Ocean Best Practices"). Indeed, arriving at a more universal set of best practices may entail going through "commonly accepted and well documented" practices, which must be then compared and synthesized (if possible).

Standards have the same objectives as best practices, but the difference is that they may serve as benchmarks for evaluation in addition to being processes. Also, they are generally top-down and may become mandatory legislated standards, such as the European INSPIRE legislation[4]. The International Standards Organization (ISO) defines standards as "documents of requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose." The time

Abbreviations: ASFA, Aquatic Sciences and Fisheries Abstracts; CMEMS, Copernicus - Marine Environment Monitoring Service; DOI, digital object identifier; EMSO(-ERIC), European Multidisciplinary Seafloor and water column Observatory; EOVs, Essential Ocean Variables; ERIC, European Research Infrastructure Consortium; EuroGOOS, European Global Ocean Observing System; EuroSites, European Ocean Observatory Network (FP7 project); FAIR, Findable, Accessible, Interoperable, Re-usable; FixO3, Fixed-point Open Ocean Observatories network (FP7 project); FOO, Framework of Ocean Observing; FP7, Framework Programme 7 (of the European Union); GEO, Group on Earth Observations; GOOS, Global Ocean Observing System; GO-SHIP, Global Ocean Ship-based Hydrographic Investigations Program; GROOM, Gliders for Research Ocean Observation and Management; HAB, Harmful Algal Bloom; IFREMER, Institut Français de Recherche pour l'Exploitation de la Mer; ICES, International Council for the Exploration of the Sea; IEEE, Institute of Electrical and Electronics Engineers; IMOS, Integrated Marine Observing System (Australia); IOC, Intergovernmental Oceanographic Commission; IODE, International Oceanographic Data and Information Exchange; IOOS, Integrated Ocean Observing System (of United States); ISO, International Standards Organization; IT, Information Technology; JCOMM, Joint Technical Commission on Oceanography and Marine Meteorology; JERICO, Joint European Research Infrastructure network for Coastal Observatory; MOOC, Massive Open Online Course; NetCDF, Network Common Data Form; NWP, numerical weather prediction; OGC, Open Geospatial Consortium; OBPS, Ocean Best Practices System; OceanSITES, Worldwide system of long-term, deep water reference stations measuring many variables and monitoring the full depth of the ocean; OOI, Ocean Observatories Initiative (of United States); OTGA, OceanTeacher Global Academy; PIRATA, Prediction and Research Moored Array in the Atlantic; QA/QC, quality assurance/quality control; QARTOD, Quality Assurance of Real-Time Oceanographic Data; RAMA, The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction; RT, research topic (used in the context of a journal); SDG, Sustainable Development Goals; SDO, Standards Development Organization; TOGA-TAO, Tropical Ocean Global Atmosphere program - Tropical Atmosphere Ocean; TPOS, Tropical Pacific Observing System; TRL, Technology Readiness Levels; UNESCO, United Nations Educational, Scientific and Cultural Organization; WMO, World Meteorological Organization.

[2]http://www.oceanobs09.net (accessed February 3, 2019).

[3]http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114 (accessed January 22, 2019).

[4]https://inspire.ec.europa.eu/inspire-legislation/26

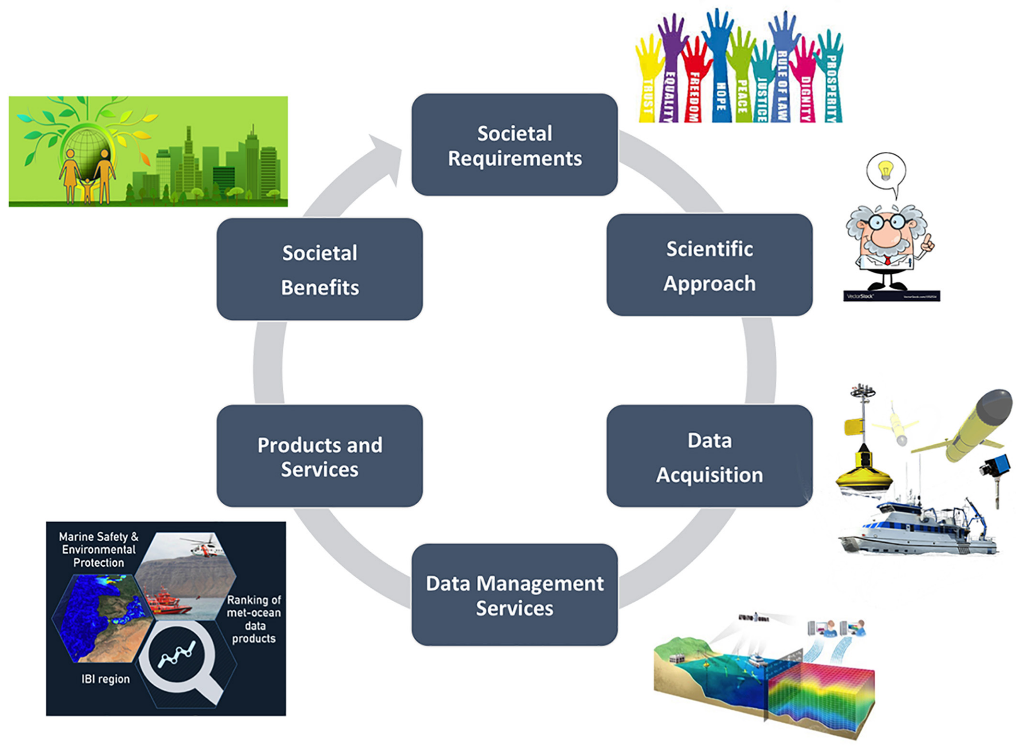

FIGURE 1 | Ocean observing value chain from requirements to societal benefits.

for the formation of a standard by a Standards Development Organization (SDO) is 3–5 years or more using formal working groups to write the standard.

The top-down approach as used in standards development can be useful to achieve a long-term, stable consensus in interfaces and certain underlying processes. There are numerous SDOs creating global, open technology standards. These include, for example, the ISO, the IEEE Standards Association (IEEE-SA) and the Open Geospatial Consortium (OGC). OpenStandards.net provides an overview of SDOs[5]. SDOs adhere to equitable methodologies for standards development, but each can have different operating practices. For example, ISO is a global network of the foremost standards organizations of participating countries; there is only one member per country.[6] On the other hand, IEEE-SA and the OGC are standards organizations that include a broad representation of industry, other organizations and individuals. The latter also have more flexibility to streamline the standards development process.

Both IEEE-SA and ISO recognize the benefits of having "recommended practices" (IEEE-SA) or "technical specifications" (ISO) – documents that address work still under technical development. Within ocean observing, there is a necessity for both standards and best practices. Generally, the bottom-up approach of ocean observing and lack of a central mandating authority such as the World Meteorological Organization (WMO) is consistent with creation and use of best practices. However, within the marine community, there is extensive use of standards. A good example is the IEEE 802.11 standard for wireless modems. For ocean observing, OGC has the Sensor Observation Service (SOS) standard to improve interoperability of sensor data management, which allows querying observations, sensor metadata, as well as representations of observed features.[7]

THE OCEAN BEST PRACTICES SYSTEM (OBPS) AND ITS IMPLEMENTATION

The OBPS is a new system comprising technological solutions and community approaches to enhance management of methods as well as support the development of ocean best practices. The OBPS includes a persistent document repository with enhanced discovery and access capabilities, a peer-reviewed journal research topic, and training approaches leveraging social media and the use of OceanTeacher Global Academy (OTGA).

The Issues for Ocean Best Practices

Ocean best practices face similar challenges to those in any other discipline – limited awareness of existing practices, lack of widespread distribution of practices, missing incentives that

[5] http://www.openstandards.net/

[6] https://www.google.com/search?client=safari&rls=en&q=ISO+organization&ie=UTF-8&oe=UTF-8

[7] http://www.opengeospatial.org/standards/sos

drive community building and lack of a centralized resource for submitting and accessing best practices.

Further, requirements on ocean observing may vary depending on mission and the ocean environment, e.g., ocean best practices for the Arctic may not be applicable to the Tropics while those that excel in coastal area may have little value in the deep ocean. A targeted measurement precision, and thus the recommended best practice, is different if one seeks to observe small climate signals in the deep ocean or monitor near real time observations in the coastal area. The variability in requirements can be so profound that they inhibit collaboration between communities. Likewise, variability of human and technology capabilities across institutions or countries may prevent global application of best practices. Documentation of best practices may also differ across sectors such as research institutions and private sector organizations. Sensor and platform manufacturers have competitive pressures to provide documentation on their products, but not necessarily with the level of detail needed for creating best practices. There is also a resistance to adapt to the latest best practices that may lead to an increase in sensor or platform non-recurring engineering costs.

Another issue for broad adoption of best practices is that they have often been passed along through direct training and through oral traditions, in lieu of written and openly distributed documentation. Additionally, in the academic community, publication of methods is not as highly regarded as publication of original research. With publication in a scientific journal, wide distribution of best practices is still not assured because many journals are behind subscription barriers despite the growing mandate for open access publishing models.

Even when methods are documented, the review process across communities is not consistent. One way to overcome this shortcoming is through a community-wide acceptance of the need for ocean best practices peer review in line with peer review of science results. Large networks, such as Integrated Ocean Observing System (IOOS) in the United States (U.S. Integrated Ocean Observing System, 2014) and the Australian Integrated Marine Observing System (IMOS) have historically been able to motivate and support peer review internally when it is an organizational priority. Smaller institutions may not have the capability because they do not have access to a wide community of readily motivated independent experts.

An alternative to the bottom-up peer review is to have an organization with a top-down coordination mandate. This been successfully applied in the field of atmospheric observations for Numerical Weather Predictions (NWP), under the auspice of the WMO. Weather observation and forecasting have a widely understood benefit for society, which is accepted and supported by governments. Atmospheric observations for NWP are coordinated through governmental agencies and based on globally agreed upon methods encoded in WMO standards. For oceans, such top-down approaches occur where a direct societal application is linked to observing, as for example, in ecosystem management for fisheries though the intergovernmental marine science organization ICES.

For other oceanic cases, as the GOOS that currently operates on rather loosely defined observing objectives and based on voluntary activities, such a structured and globally agreed mandate process does not exist. Nevertheless, ocean observing networks, which operate under the GOOS umbrella, may have created community agreed best practices documentation. GO-SHIP (Hood et al., 2010; Talley et al., 2016) has created well-defined standard operating procedures, which are propagated throughout the project. This is true, but to a lesser extent, with Argo (Roemmich et al., 2009) and OceanSITES (Send et al., 2010). Smaller networks without the breadth of resources and participation have a harder time creating broadly reviewed practices.

In summary, there are many challenges in creating and adopting practices at a regional and global scale. These include both technical and human factors that need to be addressed by the OBPS.

Introduction to OBPS and Description

The Ocean Best Practice System (OBPS) provides a foundation upon which the ocean community can more systematically develop and use best practices (Pearlman et al., 2017). The OBPS is centered on a core vision and mission (Simpson et al., 2018). It envisions having "agreed and broadly adopted methods for every activity in ocean observing from research to operations to applications." The mission statement that corresponds to the vision is "to provide coordinated, sustained global access to methodologies/best practices across ocean sciences to foster collaboration and innovation." The OBPS that was created to support this vision and mission is shown in **Figure 2**. At the heart of the system, the OBPS repository derives from expanding the scope of the OceanDataPractices Repository initiated in 2014 (Simpson, 2015). The repository software provides a secure home for the collection of documents stored in the system. Repository content can be annotated through defined metadata fields, enhancing structured archiving and retrieval. Further, submitters are encouraged to use document templates to improve consistency of the document formats and enable improved tools to be developed[8]. The repository's content is indexed by all the major search engines and harvested by such services as Google Scholar, Scopus, OpenAIRE, ASFA, etc. To support such indexing, the repository assigns DOI to submitted best practices[9]. If documents already have DOIs assigned to them by an external system, their existing identifiers are added to the system and are used as the preferred DOI within the OBPS.

Peer review of documents stored in the OBPS repository is supported through a partnership with the *Frontiers of Marine Science*. There are many forms of peer review (Walker and Rocha da Silva, 2015) and the *Frontiers in Marine Science* provides an open access platform and identifies reviewers for accepted articles. This was judged to be an important part of the community forum process desired for OBPS in that it would help build consensus around what is indeed "best" in different settings. However, peer review will not always resolve issues among competing practices, or determine at what point a new practice should replace an existing one.

[8]https://www.oceanbestpractices.net

[9]https://www.doi.org (accessed February 4, 2019).

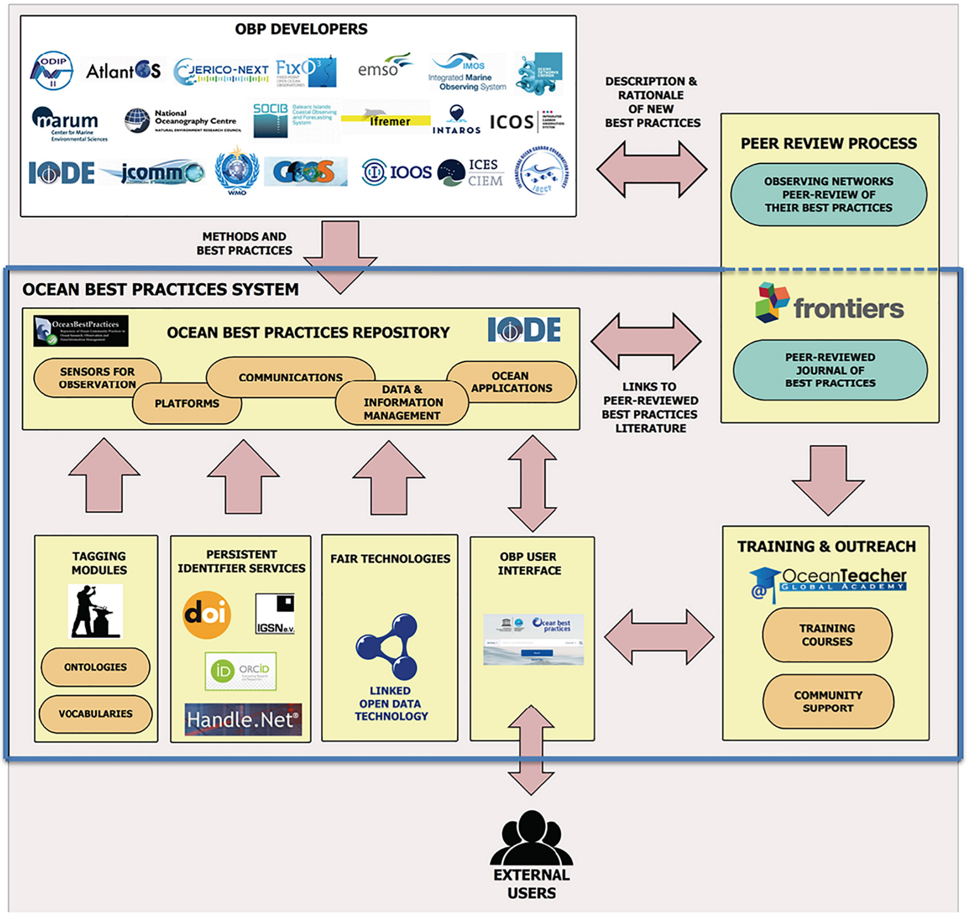

FIGURE 2 | OBPS structure (large box across middle of figure), core technologies (along the bottom of the box), and best practice provider organizations (in the box at top). Training is shown at the bottom right.

In addition to the peer review offered by academic journals, the review of submissions by expert panels from programs like GOOS[10], the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM)[11], the International Oceanographic Data and Information Exchange (IODE)[12], and others, will help identify recommended practices for respective stakeholders. GOOS has identifed EOVs as a good starting points to develop and demonstrate an expert panel process, as the EOVs support current and pressing needs for global observation. Based on the experience in implementing this process for the GOOS EOVs the precedents can be refined for use by other groups.

An archive of best practices would be of little use if it did not support training of ocean observers and users. For the training component, OBPS leverages the OTGA. This addresses all levels of professional development with the objective to support young professionals and also those who are entering or working across disciplines. With the continuing advancement of personal communication technologies and social media, there are many more opportunities to augment traditional classroom training.

To understand the details of the OBPS implementation, the system requirements guiding the design will be reviewed first.

Requirements for the Ocean Best Practices System

The long-term requirement for the OBPS came from the ocean observation community through a series of workshops and town hall meetings. Foremost among these requirements is to serve as a global focal point for ocean best practices. The more detailed requirements include:

(1) System infrastructure requirements:
- Operations should be sustainably supported.
- Open architecture should provide adaptability to future developments; mechanisms should be available to update components and procedures on a timely basis as experience grows and new technologies/methods come on-line.
- Data, information, and software hosted by the system should be open source and guided by the FAIR principles for making data and best practices more findable, accessible, interoperable and reusable (Wilkinson et al., 2016).

[10]http://www.goosocean.org
[11]https://www.jcomm.info/index.php?option=com_content&view=article&id=150&Itemid=97
[12]https://www.iode.org

Openness and transparency should be embedded in the design and operation of the system.

- Intellectual property of providers should be respected; depositing content into an open access OBPS repository on a non-exclusive basis allows the provider to retain ownership (copyright) which preferably should be indicated by a Creative Commons License[13], with the use permissions attached to the document.
- Peer review should be facilitated and encouraged.
- Training and user needs should be supported for developed and developing countries.

(2) Requirements set by system users (best practice providers and best practice end users):

- The repository should be populated with a sufficient number of best practices entries for users to want to use the system.
- Users should be able to discover and more effectively compare practices.
- The search, augmented by semantic technology, must be intuitive and easily done by non-experts.
- Maturity levels of best practices should be identified based on consistent, reproducible processes.
- The level of effort needed to submit documents to the system should be minimized and, where possible, automated metadata and content ingestion using a template should be available.
- Unique identifiers should be assigned to all practices including updated versions.
- Expanded metadata should include indicators for EOVs and SDGs, as well as the maturity of the practice.
- Access statistics/metrics for a practice should be available to providers and users.

By implementing these, the primary functionalities of the OBPS provide for: (1) contributions (both by a provider and from web inputs); (2) use (including discovery and access and comparisons of documented practices); (3) review (completeness, peer review, and updating); (4) training; (5) unique identification of documents and authorship; and (6) metrics for impact and visibility of uptake.

Approaches to Meet OBPS Requirements

Advanced technology has been incorporated into the repository to improve coherent discovery of documents with diverse formats. Search and indexing capabilities were extended into the text within each document to tag user identified words via text mining and natural language processing techniques (**Figure 3**). The OBPS Search Interface[14] presents a user-friendly portal to make use of both the indexing and the terminological tags generated by the system, offering enhanced access through FAIR-aligned interoperability solutions.

From an IT perspective, the tagging capability supported by FAIR-aligned terminology resources is an innovation that has a two-way effect. On the one hand, the reference terminologies (Buttigieg P.L. et al., 2016) help connect the content of best practice/method description documents with widely-used, machine-readable descriptors commonly applied to data. On the other hand, the text-mined content of the OBPS collection can serve to identify and fill gaps in the terminologies. Through the OBPS, there is a two-way benefit in both (1) vocabularies such as the widely adopted British Oceanographic Data Centre vocabularies[15] and (2) ontology resources covering a broad range of disciplines such as environments (Buttigieg P. et al., 2016), populations and communities (Walls et al., 2014), devices and protocols (Brinkman et al., 2010), chemicals (Degtyarenko et al., 2008), qualities (Mabee et al., 2007), and the SDGs (Buttigieg P.L. et al., 2016), all developed using the best practices of the Open Biological and Biomedical Ontologies (OBO) Foundry and Library (Smith et al., 2007). The feedback process has already seeded new research initiatives in ocean-oriented artificial intelligence, aiming to build stronger links between the vocabularies, thesauri, and ontologies deployed in the OBPS. These developments are a means to prepare the way for future integration and extended discoverability as new ocean observing capabilities emerge.

In addition to the new search capabilities, other features support scientists working out of their specialty or students looking for best practices and standard methods. Users new to ocean observing will want to know, for example, the maturity of a best practice. One maturity assessment tool is TRL which was a scheme developed in the 1970s by NASA (Heder, 2017). The number of TRL levels that are useful varies with the application (Olechowski et al., 2015). NASA uses nine levels. The FOO uses both a nine level and a reduced scale with three levels: concept demonstration (immature), demonstration (pilot) and operational capability (mature) (also used in GOOS, 2018)[16]. Similarly, current best practices vary from "mature" monitoring of certain physical parameters (e.g., temperature), and less mature methodologies (e.g., zooplankton biomass and diversity). Depending on the system or process element, the definitions of mature and immature are not always easy to articulate consistently (Ferguson et al., 2018). OBPS will use the following definitions that have been adapted from the FOO to address best practices:

- Mature: Methodologies are well demonstrated for a given objective, documented and peer reviewed; methods are commonly used by more than one organization.
- Pilot or Demonstrated: Methodologies are being demonstrated and validated; limited consensus exists on widespread use or in any given situation.
- Concept: A methodology is being developed at one institution(s) but has not been agreed to by the community; requirements and form for a methodology are understood.

These definitions have been included in **Table 1**. Assignment of maturity levels is incorporated into the best practice templates

[13]https://creativecommons.org/licenses/

[14]www.oceanbestpractices.org

[15]https://www.bodc.ac.uk/resources/products/web_services/vocab/

[16]http://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=17466

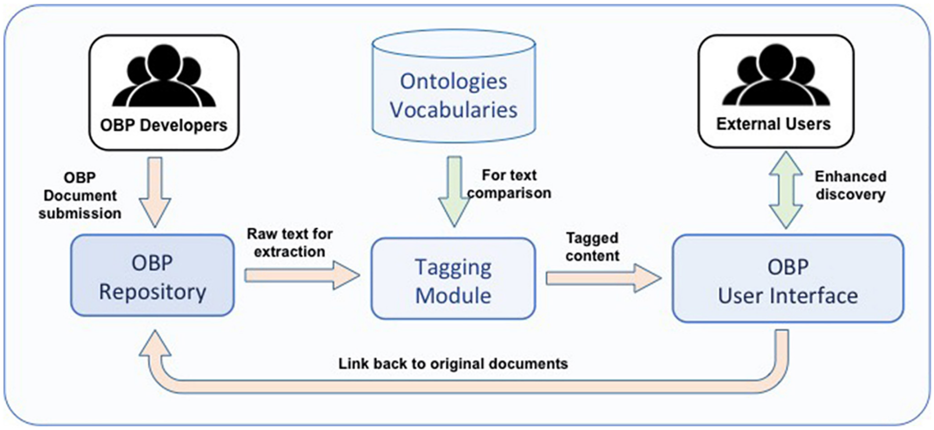

FIGURE 3 | Tagging documents using marine related ontologies enhances best practice discovery. Documents are submitted to the repository and text in the document is sent to the tagging module, which identifies tagged words by comparing with marine and other ontologies and then transmits the results for access by users.

TABLE 1 | Definitions of maturity levels for ocean best practices.

Maturity	Observations*	Data and information*	Best practices
Mature Includes Technology Readiness Levels 7–9**	Following validation of observation via peer review of specifications and documentation; system is in place globally and indefinitely	Validation of data policy via routinely available and relevant information products	Methodologies are well demonstrated for a given objective, documented and peer reviewed; methods are commonly used by more than organization
Pilot or demonstrated Includes Technology Readiness Level 4–6	Establishment of international governance mechanism; international commitments, and sustaining components; maintenance and servicing logistics negotiated	Data management practices determined and tested for quality and accuracy throughout the system; creation of draft data policy	Methodologies are being demonstrated and validated by one institution; limited consensus exists on widespread use or in any given situation
Concept Includes Technology Readiness Level 1–3	The system is articulated; capability is documented and tested. Proof of concept validated by a basin scale feasibility test	Data model is articulated. Expert review of interoperability strategy. Verification of model with actual observational unit.	Requirements and form for a methodology are understood A methodology is being developed at one institution(s) but has not been addressed by the community, or may not be written down in a coherent fashion

**From Figure 8 of Framework on Ocean Observing (Lindstrom et al., 2012). **Technology Readiness Levels 1–9 are from the Framework of Ocean Observing and are grouped here into three categories to facilitate ease of use for application to best practices.*

and is part of the metadata submission to the repository completed by the author(s). For authors to be consistent in their assignment of maturity levels, there may need to be more descriptive details of each maturity level. These could, for example, include assessing the maturity level from auxiliary information such as details about the review process (open review, number of comments received, number of experts that reviewed the document,...) and other factors. This is still under consideration.

Another important innovation of the repository is the introduction of templates to create greater uniformity in the formats and descriptions of best practices; this will be instrumental for improving technological enhancement for the whole system, as described above. The templates offer a suggested structure for best practice documents as well as a comprehensive metadata sheet. At present three templates are offered (sensors; ocean applications, data management) and more are under development. Depending on their subject and/or domain of relevance, the templates include different elements. The OBPS sensor template, for example, includes sections for calibration and deployment. Through such templates, best practice providers will be able to take advantage of automatic ingest of the metadata and document content into the repository with just one upload click. Concurrently, digital technologists will have a more workable and predictable foundation to further enhance the system with new features and components.

The many benefits that the repository offers to both best practice providers and users are listed in **Table 2**.

Peer Review Process

Peer review is an important part of broadening acceptance of methods. The OBPS will accept submissions from a wide base of practitioners and, given personnel capacity, undertakes light quality checks to ensure content is relevant and intelligible; the author is still responsible for the accuracy of content. Across ocean sciences, peer review of methods is done in different ways by different programs and networks. For those not engaged in the larger ocean observing networks, generally under the JCOMM umbrella, ways to approach best practice review are unclear. Thus, it was recommended at the Ocean Best Practices Workshop

TABLE 2 | Ocean best practices provider and user benefits.

Best practice provider benefits	Best practices user benefits
Content Indexing by all major search engines	Consolidated access to best practices hosted in a living, sustained system (oceanbestpractices.org)
Content tagging for improved discovery and use	Easily discoverable and comparable content, powered by ocean-focused search and indexing technology
Digital object identifier issued for improved citations	Notification services to keep track of updates
Associated peer reviewed papers (Frontiers research topic)	Peer review and community forums provide insight and commentary
Simple submission process supported by templates	Access to best practices relevant to sustainable development goals and essential ocean variables
User metrics	Feedback on use/metrics
Engagement in community dialogue	Training in best practice use and creation

in November 2017 (Simpson et al., 2018) that the OBPS should provide the ability to publish ocean best practices (methods) and related documents in a recognized journal. This resulted in the establishment of a *Research Topic* (RT), also known as a "Special Issue" entitled *"Best Practices in Ocean Observing"* in the journal *Frontiers in Marine Science - Ocean Observations*[17] The Frontiers journal was selected because it offers open access to published articles (via an author's publishing fee), a timely review and publication process, and the possibility for commenting on published research through a commentary tool available at the publishers' website. Thus, it provides an opportunity for wider exposure of methods documentation. Moreover, best practice provider groups have the opportunity to publish their results in peer-reviewed literature, thus making it recognized for standard research performance metrics and professional advancements. The RT peer review process is rigorous and is an element of best practice community review.

Other methods of community peer review are also part of the recognition process. Large networks such as the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) provide internal peer review by their experts. Projects such as FixO3 and JERICO in Europe have done peer review using project participants and IOOS in the United States uses program participants and panels. For EOVs, GOOS Panels[18] are also assessing review procedures to identify "recognized" methods that support the monitoring of EOVs. Best practices that have undergone these reviews or publication in the RT are identified as peer reviewed in the repository.

Training and Knowledge Transfer

Adoption of best practices is an increasing and pressing concern of global science. For example, the number of scientists involved in ocean acidification research has increased rapidly over the past few years due to the urgent need to better understand the effects of changes in carbonate chemistry on marine organisms and ecosystems. It then became necessary to establish common procedures recognized by experts for the measurement of carbonates, in particular in order to educate inexperienced young scientists entering this field of study (Riebesell et al., 2011). In other words, best practices form a means to transfer techniques and approaches from experts to new practitioners in developed and developing countries (Bax et al., 2018).

Within OBPS, capacity development and training is being implemented through the IOC OTGA[19] operated by IODE in collaboration with other training efforts in the ocean observing community (Miloslavich et al., 2018b). The IODE was certified as a Learning Services Provider in April 2018 (ISO 29990). The training is initially planned as a series of in-person courses consistent with the OTGA Regional Training model (IODE/IOC, 2016), which will cover the use of best practices on sensors, applications, data management and other topics. Courses will be offered in response to stated community needs. The classes benefit the individual participants and become more valuable if the participants become trainers. To that end, train-the-trainer courses will be offered. The repository accepts videos for training with the longer-term goal of creating a library of remote best practice training resources that would be used in a blended training environment (personal and virtual). Video training on the use of the repository is in the planning stage.

In addition to the courses directly linked to the OBPS, summer schools based on ocean observing methods and other opportunities will promote the system and encourage students, technicians and scientists to use best practices and provide feedback to the best practice providers.

IMPLEMENTATION EXAMPLES

The discussion of methodologies can become very abstract to non-specialized practitioners. Concrete illustrations of the creation, adoption and routine employment of best practices are necessary. For this paper, three practices along the value chain have been selected: (1) a HAB assessment product (see section "Harmful Algal Bloom (HAB) Forecast Services"); (2) guides for Eulerian platforms (see section "Global Eulerian Observatories Networks"); and (3), a sensor best practice to measure oxygen in the ocean (see section "Oxygen Data Accuracy for Sensors on Argo Floats"). In addition, the observations monitoring (see section "Assessing the Performance of Ocean Monitoring Systems") as well as the quality assurance and quality control (QA/QC) of data (see section "Quality Assurance/Quality Control") are crosscutting issues that are also included in this section.

[17] https://www.frontiersin.org/research-topics/7173/best-practices-in-ocean-observing

[18] http://www.goosocean.org/index.php?option=com_content&view=article&id=11&Itemid=111

[19] https://3iiz1x2nd4vl3b8ewe4frxdf-wpengine.netdna-ssl.com/wp-content/uploads/2016/03/Ocean-Teacher-Global-Academy-Brochure.pdf

Harmful Algal Bloom (HAB) Forecast Services

Harmful Algal Blooms occur when colonies of algae grow out of control and produce toxic or harmful effects on people, fish, shellfish, marine mammals and birds. The Irish Marine Institute HAB forecasting bulletin is an example of a successful application and documented best practice developed to actively support end-user aquaculture farm management decisions. Other HABs reports are issued routinely for the Gulf of Mexico[20], the Great Lakes and California in the United States and through CMEMS for Europe[21].

The HAB forecast is created using *in situ* ocean observations, numerical modeling and remote sensed satellites observations to create useful science-based products that are visualized as maps and plots. This is a good example of an application reaching across the entire value chain from observations to providing a product to an end user. For the end-product, the forecast and associated risk is determined by a local expert to provide a coherent national/regional early warning system based on best practices across a range of methodologies.

Searching for "Harmful Algal Bloom" reveals currently[22] 58 documents in the oceanbestpractices.org repository. Twenty-four of those documents were published between 2015 and 2018 and are distributed between local/regional practices[23] and global IOC manuals and guides. Authors for the documents are generally experts in their fields either from academia or members of a local government. An exemplar of what is done by the Marine Institute of Ireland for their HAB forecasting bulletin has been entered into the OBPS repository (Leadbetter et al., 2018).

There are a number of challenges in developing the HAB forecasting bulletin. The first is that, because of the complexity of HABs, there is no single "best" practice at the global level, i.e., regional circumstances matter. (Anderson et al., 2018) The OBPS repository, by providing broad access to community practices used to predict HAB dynamics, offers the potential for productive improvements in the forecast capabilities regionally.

Global Eulerian Observatories Networks

The Eulerian (also known as moored or fixed point) observatory infrastructure is moored to the sea floor but may reach upward to/across the ocean surface. There is great variability in the design and implementation of these observatories in terms of both technologies and methods (Coppola et al., 2016). The infrastructure can include very simple to complex/power-hungry sensors supporting a wide range of marine disciplines. Real-time data access can be available from cabled sites or via surface telemetry buoys.

The management of individual Eulerian observatories is primarily in national (institutional) hands but multinational consortia exist that coordinate the infrastructure for regionally optimized observing approaches, such as the European EMSO-ERIC (formerly FixO3), Tropical Arrays (e.g., PIRATA) and Regional Alliances such as IMOS. Driven by the wide variability, almost all consortia have created their "own" best practices for sensors, infrastructure, and data that are tailored to their needs. Many of them are based on field experience and personal and institutional expertise.

Given the national or consortia driven operation of the infrastructure, Eulerian observatories documentation is highly fragmented. Under the umbrella of the global Eulerian observatory network OceanSITES, community agreement has been achieved for selected best practice segments such as data dissemination. The OceanSITES data policy and the OceanSITES NetCDF data file format and file dissemination are important achievements. However, even for the data dissemination, some of the biological and biogeochemical data that need complex, comprehensive documentation on methods and agreement from a global community have not converged (e.g., sediment trap data).

Searching the OBPS repository for Eulerian observatories related keywords[24] Eulerian (19), OceanSITES (27), FIXO3 (7), Mooring (151), PIRATA (11), RAMA (9), TPOS (3), TOGA-TAO (5), EMSO (5), EuroSites (2), and OOI (7) revealed the existing documentation (number of documents given in brackets). This is a major achievement of the repository as a similar search would not be possible with other search engines. Another benefit of the OBPS is that best practices can be paired with other documentation that deal with generic techniques (e.g., conversion of acoustic backscatter intensity into target strength) relevant to Eulerian observatories in order to produce a broad harmonization of applicable practices.

In order to best leverage the investments in Eulerian observatories, regional and global coordination is mandatory. The integration is closely linked to appropriate best practices and their documentation regarding sensor handling, analysis techniques, or data reduction. This includes for example, data from sediment traps (carbon export), air-sea fluxes measured by the surface buoys, or all types of quality control data. With increasing maturity of sensors (e.g., pH, pCO2, zooplankton imagery) and emerging techniques (e.g., 'omics'), new best practices will need to be created. Documentation of these practices in the repository will support enhanced harmonization across the Eulerian observatories networks on a regional to global scale.

Oxygen Data Accuracy for Sensors on Argo Floats

Accuracy for oxygen sensors has been improved during the last decade through the efforts of the Argo-oxygen community (Thierry et al., 2018b). The main advances came from intensive characterization of oxygen sensors by different groups (Bittig et al., 2018) and the creation of documented best practices. The target that was set at the OceanObs'09 for scientific exploitation ($1\ \mu mol\ kg^{-1}$) for open ocean studies (Gruber et al., 2010) can now be achieved if full attention is given to the recommendations on sensor calibration (pre- and/or post-deployment) as well as

[20]https://oceanservice.noaa.gov/news/redtide-florida/welcome.html

[21]http://marine.copernicus.eu/usecases/harmful-algae-bloom-monitoring-aquaculture-farms-spain/

[22]Visited 1. April 2019

[23]Ireland (2), US (2), EU (3)

[24]See abbreviation list for full names of these systems or programs.

sensor performance validation during deployment, e.g., by in-air referencing (Bittig and Körtzinger, 2015). Searching for "oxygen optode" and "Argo" currently[25] in the OBPS repository result in 16 documents.

Thanks to the Argo community work, three important practices have been documented: the calibration protocol for optodes[26] (Moore et al., 2009) performed by manufacturers has been enhanced toward a multi-point calibration procedure[27]; a data processing and qualification chain has been defined in a best practices manual (Thierry et al., 2018a); and a guide has been written for the mounting of sensors on Argo platforms to enable in-air sampling (Bittig et al., 2015)[28]. Where it can be used, the in-air sampling constrains the oxygen optode *in situ* drift over time (Bushinsky et al., 2016; Bittig et al., 2018). In this case, the relation between the scientific community and industry (e.g., Aanderaa, Sea-Bird, NKE) allowed improvement of the technology in order to satisfy the recommended best practices (Bittig et al., 2015). Optode in-air observations throughout the Argo float deployment are the most recent best practice recommendations proposed by the Argo community (Bittig et al., 2015) and they considerably improve accuracy (Bittig et al., 2018) and are a key to achieving the OceanObs'09 goal for scientific exploitation. The best practices have been contributed to the OBPS to give them better visibility to the broader community.

Assessing the Performance of Ocean Monitoring Systems

There is a need to optimize the investments in ocean observing and to understand how marine monitoring data and information can be effective and reliable for developing societally relevant products. The first community-based best practice for monitoring systems that incorporates end-user products has been developed by the European Marine Observation and Data Network[29]. The practice, called a "Sea-Basin Checkpoint"[30], produces an assessment of monitoring systems at the scale of the European Seas. An essential component of the Sea-Basin Checkpoint framework is the definition of assessment criteria and their measurable indicators.

A unique Checkpoint assessment best practice was developed for three European sea basins (North Atlantic, Mediterranean Sea, and Black Sea). The results for these basins demonstrated that the Checkpoint assessment is feasible and has led to a promising methodology (best practice). During the development, several challenges were encountered in creating the best practice. One was the establishment of a proper end-user product specifications and the evaluation of the monitoring adequacy on the basis of comprehensive indicators (Pinardi et al., 2017). Another challenge was to have a sufficient number of end-user products to estimate the data and information adequacy across application sectors.

In the short term, the Sea-Basin Checkpoint assessment framework has to gain acceptance by a larger community. The methods for the Mediterranean Checkpoint have been documented in the OBPS repository (Manzella et al., 2017) to encourage review and dialogue of these methods. In this manner, the OBPS becomes one of the elements for expanding monitoring from a scientifically based network to an operational system.

Quality Assurance/Quality Control

There are two elements to quality management: quality assurance and quality control. Quality assurance can be defined as "part of quality management focused on providing confidence that quality requirements will be fulfilled." Quality control can be defined as "part of quality management focused on fulfilling quality requirements." While quality assurance relates to how a process is performed or how a product is made, quality control is more the inspection aspect of quality management[31].

The metrological traceability of ocean measurements is an important element of QA/QC. Too often, operators of platforms fully rely on calibrations carried out by manufacturers and are not able to carry out independent quality checks and changes as *in situ* conditions are not accounted for. This is due to a lack of agreed upon methods across different observing programs. Harmonizing QA/QC procedures for the collected data across different observational programs is essential.

The best practice creation process at a component or system level starts with documenting all integration, design details and routine maintenance procedures. It is also critical to document real-time data QA/QC. In formulating quality control best practices, the breadth of the challenge requires many detailed manuals, each focused on a different facet of quality control[32]. Over the last decade, many such manuals were created and peer reviewed. These are all available in the OBPS repository.

The implementation of this quality assurance strategy on a global level will need the support and concurrence of international organizations such as GOOS, IODE, and JCOMM. As quality control harmonization progresses, the FAIR compliance of the OBPS repository will simplify and motivate coherent discussions and help consolidate quality control approaches across the observing community.

Beyond Implementation Examples

This section has shown that OBPS addresses many aspects of the data life cycle from the point of observation all the way through data products and services, providing needed visibility for these best practices. The OBPS is a living system and contains many practices that can facilitate interoperability and coordination across networks. A challenge for the OBPS project is to convince the ocean community of the benefits of harmonizing the processes and outcomes of ocean observing.

[25] Visited 1. April 2019

[26] Optodes are optical instruments for ocean monitoring.

[27] https://www.ferrybox.org/imperia/md/images/hzg/institut_fuer_kuestenforschung/koi/ferrybox/fb_workshop2016_o2kalibrierstand_finish_tina.pdf

[28] see also SCOR WG 142: Quality Control Procedures for Oxygen and Other Biogeochemical Sensors on Floats and Gliders. Recommendation for oxygen measurements from Argo floats, implementation of in-air-measurement routine to assure highest long-term accuracy.

[29] http://www.emodnet.eu

[30] http://www.emodnet.eu/checkpoints

[31] https://asq.org/quality-resources/quality-assurance-vs-control

[32] https://ioos.noaa.gov/project/qartod/

FUTURE VISION FOR OCEAN BEST PRACTICES

To enable broad adoption of best practices, advances in technology play an important role as well as other considerations such as community engagement (involving providers and users of observation data), governance and training/outreach. This section will look at potential advances during the next decade and then address how the management of methodological expertise and the development of best practices should evolve to serve the ocean observing community.

The Evolving Ocean Observing

Virtually all of the prominent advances expected in the coming decade contribute to the vision of "a truly global ocean observing that delivers the essential information needed for our sustainable development, safety, well being and prosperity"[33]. Selected present and future developments across the value chain that will drive future best practices are shown in **Figure 4**. They can be grouped into three categories: hardware, data and software, and human factors and frequently feature exchanges with other disciplines. For hardware and software implementation in ever more complex scenarios, standards and best practices for engineering are vital assets for upcoming generations. To illustrate, consider that oceanographers have faced three persistent technology-related challenges over the past half-century: limited electrical power, challenging data telemetry and sensor calibration (predeployment and during *in situ* operations). Practices relating to power usage and communications optimization are many times done by individual programs and benefits from this work would be gained by making such methodologies more broadly available. Improving the transfer of technology from other fields such as batteries from electric vehicles and sensors from mobile phones will expand options for observing systems. With such transfers, the adaptation of technology will need guidelines and methods that are adoptable by multiple organizations.

As seen in **Figure 4**, software advances such as cloud computing, the use of artificial intelligence and others will need to be supported by a new generation of documented methods. As an example, advances should occur in the seamless integration of value chain elements leading to integrated ocean observing products. Linkages across portions of the value chain are being implemented through maturing standards such as the OGC sensor web enablement (del Río et al., 2017; Buck et al., 2019). In addition, integration across disciplines and marine data types (e.g., bathymetry, benthic imagery, 'omic analyses,' expanded biological and ecosystem monitoring) will be increasingly important (Brooke et al., 2017; Picard et al., 2018; Przeslawski and Foster, 2018). As the Internet of Things emerges, linkages across systems that are remotely and autonomously configurable will increase sensor-to-sensor networking and the needs for more advanced quality control (QC) processes.

There will also be an evolution to field-capable real-time QC. This needs to include a continued and expanded international effort to develop stable, broadly used QC standards. Manufacturers will begin implementing real-time QC processes and data flagging embedded within their sensors and field components (Bushnell, 2017), so that data can be more easily integrated. OBPS will need to support these and other advances in the coming years.

OBPS Evolution

As discussed above, the growing fields of ocean research, operational oceanography and ocean services will all require an expanded set of best practices that should be guided by international consensus. Aligned with this, the OBPS has the opportunity to become a more active component in such consensus building by offering support throughout the life cycle of promising methods. This may involve the creation of "pilot" or "demonstration" projects to illustrate the best practice (and standards) lifecycle.

Ocean Best Practices System is investigating the inclusion of full text standards in the repository. Collaboration with recognized standards organizations, through the creation of working groups, will be a necessary part of this effort and will also lead to improved coherence.

Another major point of evolution is centered on the integration of best practices in the OBPS across the ocean value chain. To enable this, the inputs and outputs for each method in the system would need to include standardized (and machine readable) links between them. This would enable users to discover networks of methods across disciplinary and operational boundaries, supporting truly integrative product creation. Such linkages can be complex as seen in the HABs illustration case in Section "Harmful Algal Bloom (HAB) Forecast Services." The linkages are not one to one, but many to many as the woven threads of a fabric, paralleling development of the data fabric concept under the Research Data Alliance[34]. Based on the current ability of the OBPS to create interlinkages across documents, the application of structured document templates, more advanced natural language processing and ontologies tailored to the OBPS requirements will enable semi- or fully automated solutions for this task.

Repository

Benefiting from the developments in Section "OBPS Evolution," the repository will expand its range of services and provide interfaces with resources in other infrastructures in the coming years. The descriptions of best practices through its associated metadata will be expanded and standardized to further improve search and access. Further, existing templates will be updated to render their contents more machine actionable. The repository will also develop approaches to link methods to any data, software or code they reference. For example, persistent Uniform Resource Locators (URLs)[35] linking methods to reference data sets hosted

[33]http://unesdoc.unesco.org/images/0026/002651/265128e.pdf (accessed October 20, 2018).

[34]https://www.rd-alliance.org/group/data-fabric-ig/case-statement/data-fabric-ig-case-statement.html

[35]https://en.wikipedia.org/wiki/URL

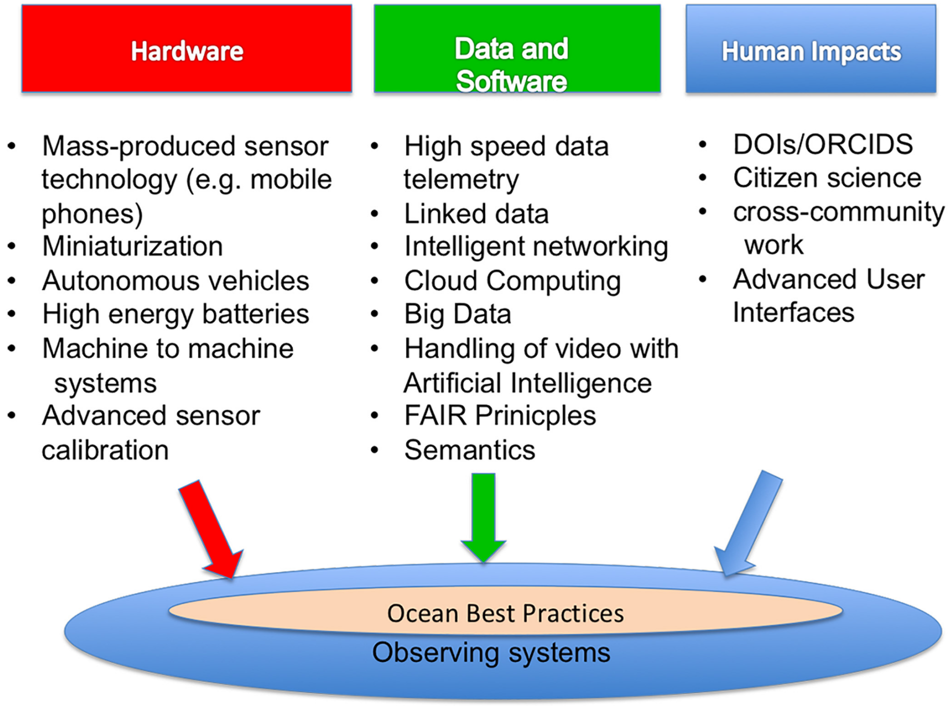

FIGURE 4 | Advances in the next decade will enhance ocean observing and impact best practices evolution.

in trusted archives will become a common feature among best practices. Further, dated links to version controlled Github repositories[36] and/or Jupyter notebooks[37] will provide software and process connectivity as well as reproducibility of software executable processes.

Finally, development of a practice is a time-consuming process (Przeslawski and Foster, 2018). To approach this more effectively, alternative media forms such as using video recording and data capture will be considered by the OBPS to enhance the documentation process. The repository will thus feature video embedding resources for content hosted through partner projects or via widely available social media systems that assure the necessary content for practices persists.

Peer Review

A process to identify preferred practices for defined applications and/or scenarios is a necessary part of the OBPS evolution. Currently, GOOS together with OBPS are developing a process to identify methods suitable to measure and report on the EOVs. To complement this review model, OBPS is exploring crowd-sourcing approaches to assess community support and adoption for methods in the system. Social media functionality including up- or down-voting coupled with commenting has had remarkable success in web platforms such as StackOverflow[38]. Indeed, several academic journals have incorporated forms of community review and hybrid models (Walker and Rocha da Silva, 2015). OBPS is exploring such hybrid systems to maximize community involvement, including through the *Frontiers in Marine Science Research Topic on Best Practices in Ocean Observing.* This Frontiers Research Topic forum is free to all for discussions of methods and comments on papers published in the journal. In the coming years, the aim is to pilot these possibilities and implement a consolidated approach for an expanded peer review model to help detect, test, validate, and ultimately update best practices as they emerge from the OBPS repository.

Training Modalities and Implementations

Expanding the use of common practices by new or expanded ocean research and application interests is a priority of the OBPS. As mentioned earlier, the system aims to support students, professionals working in cross-disciplinary collaborations and educators Looking forward and to fulfill its global mission, the OBPS must prioritize adoption of new techniques in training and capacity building capable of reaching across regions, cultures, and resources. The current OTGA approach of drawing upon ocean observation experts working with educators will be expanded. Moving beyond the traditional in-person training programs, OBPS will incorporate other community efforts such as online, multimedia-based training solutions that have been produced by ocean projects for their staff and others[39]. The OBPS will use similar web-based approaches to multiply the reach of

[36]https://github.com

[37]https://jupyter.org

[38]https://stackoverflow.com

[39]http://imos.org.au/facilities/nationalmooringnetwork/moorings-documentation/bgcwatersamplingvideos/

workshops and other events/programs such as summer schools well beyond those that have the resources to be present in person A similar effort for summer schools will provide a long-term community resource. The next stage of training using OBPS content will leverage the now refined modality of the Massive Open Online Course (MOOC)[40]. Their effectiveness has already been demonstrated by organizations such as IMOS, which has developed a MOOC focused on marine scientists for learning about ocean observing and the use of marine data[41] (Lara-Lopez and Strutton, 2019). Configuring high-quality MOOCs for different user groups will be an immense asset over time, consistently returning rewards that will soon outweigh its initial costs. These types of courses should also be configured as education content for university training and summer schools.

Moving beyond traditional classroom and video methods, a range of new tools such as visual immersion techniques as well as the use of three-dimensional computer-aided-design (CAD) drawings is envisioned[42]. There are also training opportunities to use hands-on sensor "models" created by 3D Printing (Bogue, 2016). All of these may be envisioned as some of the next steps for far-reaching training solutions.

Engagement, Outreach, and User Support

The value of any system is contingent on its relationship to its user community and scaled by the degree of its adoption. Thus, the next decade OBPS development will be accompanied by community outreach and engagement activities to make the OBPS a system that users integrate into their routine work. Visibility for ocean best practices from Google and other search engines is important. This involves general technical approaches such as search engine optimization[43], as well as building relationships with organizations and projects such that the OBPS will become integrated in their sites, increasing its exposure and connectivity in a more customized fashion.

At a finer level, interfaces will be created to report on user engagement with individual documents. A dashboard will be integrated into the OBPS user experience to convey information on how many times a document has been accessed, viewed, downloaded, and by what kind of user[44]. To move forward, a series of metrics will be defined for a best practice that could include the number of citations, the number of community "upvotes" and user feedback. This would complement a more formal endorsement process that would be done by panels of experts, providing submitters with more comprehensive insight into how their methods are being received.

While building the first instance of the OBPS, our experience at international workshops and town halls has shown that there needs to be an active user outreach effort, as many users are typically focused on methods most prevalent in their institution or immediate community of collaborators. Indeed, some may not even be aware of the concept of regional or global best practices. In response, we will continue to represent the OBPS at larger oceanography and science conferences, to demonstrate how the system can expand methodological awareness and can benefit oceanographers and others in their work. In addition, there will be sessions at specialty workshops focusing on ensuring the OBPS suits specialist needs. Less formally, monthly newsletters and reports on progress will continue to be circulated both for outreach and community building.

Governance

The long-term functionality of the OBPS will be sustained as a project within IOC/UNESCO, complemented by partnerships with major ocean observing organizations. Naturally, this model for sustainability and advancement requires an effective governance strategy that preserves, yet evolves, the system and its policies. This is particularly important as the founders of the OBPS transfer and distribute decision making to a wider group of custodians. Further, the system's governance should also allow it to easily adapt to major international initiatives such as the UN Sustainable Development Goals as well as the UN Decade of Ocean Sciences for Sustainable Development. This will involve international collaboration and innovations to meet the challenges of the next decade and beyond.

Within the ocean community, a number of governance models could exist as either top-down or bottom-up. Ocean research, as mentioned earlier, generally operates bottom-up. Service and product organizations generally work top-down. As the community moves towards more opeartional ocean products in addition to supporting research, the OBPS must have adaptable governance that supports both bottom-up and top-down. For example, the governance needs to recognize the engineering challenges such as inclusion of BPs used for system design and optimization. The OBPS should also include societal and ethics factors impacting ocean observing. One example is to include practices that support how to do a cost/benefit analysis. Another is to include practices on advice and methodologies for obtaining research authorizations, navigation rights, legal status of seabed resources or ship passage, conservation and management of marine living resources, etc. The use of animals in research requiring ethics committee approval is a subject that could be shared as best practices. Although these multiple aspects may differ from one country and continent to another, a centralized location that provides access to best practices of the complexity of these social aspects of ocean observation would benefit all communities.

Through the governance approach above, the OBPS will be able to support the large and growing diversity of scientific and societal needs faced by ocean observers and users.

[40]https://en.m.wikipedia.org/wiki/Massive_open_online_course

[41]https://open2u.utas.edu.au/Course/4261

[42]https://www.hawaii.edu/news/article.php?aId=7593

[43]https://searchengineland.com/guide/what-is-seo

[44]A thorough assessment of user privacy will accompany this process as it develops, with consultation from the OBPS user base. The intention here is to understand where and by whom a method may be most suitable or applicable.

SUMMARY AND RECOMMENDATIONS

In the sections above, key capabilities have been identified that would make a robust environment for the development, promotion, and adoption of best practices by multiple ocean communities. This section distills the above sections into a set of recommendations that we believe will allow the OBPS to evolve to meet future needs. The order of the recommendations follows the order in the above text and is not necessarily the order of priority. The implementation order will come from discussions at OceanObs'19, IOC recommendations, dialogues with experts across the value chain and inputs from the planning and evolution of the UN Decade of Ocean Science for Sustainable Development.

(1) Improving the transfer of technology from other fields will significantly improve the capacities of observing systems. Widely available and accessible guidelines and methods that are adoptable by multiple organizations are needed to support this transfer.

> Recommendation: Prioritize support for transfer and mainstreaming of advanced technologies from diverse communities through developing and promoting best practices.

(2) The linking of best practice will support more efficient research and operations product development. The challenge will be to have experts and best practice creators to help others understand the impacts of selecting one best practice over another.

> Recommendation: Create, optimize, and implement methods to link best practices across the value chain working with community experts and provide metrics and reports of the impacts on observations, modeling and end-user applications.

(3) There will be an evolution to field-capable real-time QC. With the growing use of autonomous systems and Internet of Things networking, there will be a complex evolution of platforms and sensors with interoperable, field-capable, and real-time QC. Thus, an expanded international effort to develop QC standards and best practices of all types is needed.

> Recommendation: The OBPS must develop dedicated capacities to support methods in QC, with the expectation of increasing machine-to-machine communication and (semi-) autonomous operations.

(4) A consolidated terminology resource for ocean activities across the value chain is not yet broadly available. Continued evolution of marine terminology resources, including those that are relevant to oceanography and its applications is needed. These range from sustainable development goals monitoring to genomics to aquaculture applications. The vocabulary expansion can come from words used in best practices contributions or from activities in related communities.

> Recommendation: A broader range of terminology resources with relevance to ocean activities needs to be implemented and focused on ocean research and applications.

(5) Increased automation will impact observing practices as well as OBPS operations. To keep pace, there is a need for automated or semi-automated solutions for contributing, quality controlling, reviewing and updating a special collection of best practices to the repository. Networks of autonomous vehicles and interlinked sensors are thus likely to become a virtual stakeholder group in the future of OBPS.

> Recommendation: Prepare for automated contributions to the OBPS by co-strategizing with developers of such systems and AI practitioners working with their outputs.

(6) Identifying best practices that are common across EOVs in collaboration with the GOOS Panels will help establish consolidated methods to observe EOVs that can further the creation of science-based products.

> Recommendation: With the respective GOOS EOV Panels, identify methods that are suited to delivering one or more EOVs and elevate them to best practices. Identify practices that support multiple EOVs. Then create a compendium of such best practices that can be highlighted and prioritized for community input and refinement.

(7) Transferring knowledge stored in the OBPS through training will evolve through the use of social media and more advanced communication technologies and platforms.

> Recommendation: Create a long-term strategy for training using OBPS content, leveraging the advances in social media and technology, while engaging education professionals to design effective and regionally/culturally tailored course content.

(8) Environmentalsustainability as well as interactions with societal needs and legal conventions will have important impacts on the future of ocean observing. To address this, the OBPS must link to global and regional policy frameworks such as the Sustainable Development Goals, the EU's Marine Strategy Framework Directive and ocean-focused legal frameworks such as the UN Law of the Sea Convention (UNCLOS).

> Recommendation: Engage communities in ocean and marine policy and law, offering the use of the OBPS to facilitate development and/or share best practices in the domain. In parallel, enhance OBPS technologies such that all documents can be more easily linked to applicable laws or policy directives and indicators. Further, and in preparation for the Decade of Ocean Science for Sustainable Development, focus effort on integration with systems used to advance and report on the UN Sustainable Development Goals.

These are selected recommendations for developments during the next decade. They are not complete and will certainly evolve as experience is gained in working with the OBPS and the ocean observing community at large. We invite all readers to contribute to the process ahead, ensuring the OBPS can suit their community's needs.

GLOSSARY AND DEFINITIONS

Controlled vocabularies: A controlled vocabulary is an organized arrangement of words and phrases used to index content and/or to retrieve content of documents through browsing or searching. It typically includes preferred terms in professional or common usage. The purpose of controlled vocabularies is to organize information and to provide terminology to catalog and retrieve information (extracted from http://www.getty.edu/research/publications/electronic_publications/intro_controlled_vocab/what.pdf).

Copyright: is a law that gives the owner of a work (like a book, movie, picture, song or website) the right to say how other people can use it (see also **intellectual property**).

Eulerian observations: is a way of looking at fluid motion that focuses on observations at a specific location in the space through which the fluid flows as time passes.

Faceted search: Faceted search is a technique that involves augmenting traditional search techniques with a faceted navigation system, allowing users to narrow down search results by applying multiple filters.

Intellectual property: refers to the ownership of an idea or design by the person who came up with it. It is a term used in **property** law. It gives a person certain exclusive rights to a distinct type of creative design, meaning that nobody else can copy or reuse that creation without the owner's permission; sometimes abbreviated "IP" (see also **copyright).**

Linked data: is a method of publishing structured data to the web such that it can be discovered and accessed by distributed systems and connected to related data or information through semantic references.

Machine learning: is Artificial Intelligence that enables a system to learn from data rather than through programming; the scientific study of algorithms and statistical models that computer systems use to effectively perform a specific task without using explicit instructions, relying on models and inference instead.

Metadata: Data that describes other data. Meta is a prefix that in most information technology usages means "an underlying definition or description." Metadata summarizes basic information about data, which can make finding and working with particular instances of data easier; metadata may also be applied to descriptions of methodologies.

Natural language search: is a computerized search performed by parsing a query phrased in everyday language, where the user would phrase questions as though they were talking to another human.

Observing network: is the group that coordinated a family of observing devices that operate along a rather similar technology (e.g., Spray glider, Slocum glider, Seaglider,...).

Observing system: is a system of ocean observing elements – including devices (organized in observing networks), data integration, data product generation and dissemination, requirements setting, science approach for the requirement set, etc.

Ontology: A formalized, machine-readable, and logically consistent representation of human knowledge, typically organizing phenomena into a hierarchy of categories and their instances. Categories and instances are connected through logical relationships which can be understood by machines.

Open data: Data which is freely available to everyone to use and re-publish as they wish, without restrictions from copyright, patents or other mechanisms of control[45].

Open access: refers to research outputs which are distributed free of cost or other barriers, and possibly with the addition of a Creative Commons License to promote reuse.

Open source: is a term denoting that a product includes permission to use its source code, design documents, or content. It most commonly refers to the open-source model, in which open-source software or other products are released under an open-source license as part of the open-source-software movement. Use of the term originated with software, but has expanded beyond the software sector to cover other open content and forms of open collaboration.

Peer review: is a process by which a scholarly work (such as a paper or a research proposal) is checked by a group of experts in the same field to make sure it meets the necessary standards before it is published or accepted.

Performance metrics: Metrics are quantitative measures designed to help evaluate research and operations outputs. Metrics are intended to be used in conjunction with qualitative measures such as peer review.

Repository: is an archive of documentation or objects; in this paper refers to the OceanBestPractices repository hosted at IOC/IODE of UNESCO.

Semantics: means the meaning and interpretation of words, signs, and sentence structure; the branch of study within linguistics, philosophy, and computer science which investigates the nature of meaning and its role in practical applications.

Standard operating procedures (SOP): is a set of step-by-step instructions compiled by an organization to help workers carry out complex routine operations.

Standards: are documents of requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose.

Tagging: in information systems, a tag is a keyword or term assigned to a datum or information content entity (such as a digital image, word or phrase in an electronic document or a computer file). This kind of metadata describes an item or subitem and allows it to be found again by browsing or searching.

Text mining: is the process of deriving information from text. The overarching goal is to turn text into data for analysis, via application of natural language processing and analytical methods.

Trusted: Regarded as reliable or truthful; able to be depended on for an application or analyses; can also be applied to relations between organizations or people.

[45]https://openaccess.mpg.de/Berlin-Declaration

Value chain: can be defined as the set of value-adding activities that one or more organizations perform in creating and distributing goods and services. In terms of ocean observing, the value chain approach can be applied to consider societal benefits of the data and assess the value of data and data features.

Vocabulary: A list or collection of words or of words and phrases usually alphabetically arranged and explained or defined.

AUTHOR CONTRIBUTIONS

JP, MBu, LC, JK, PB, FP, PS, MBa, FM-K, CM-M, PP, CCh, JH, EH, and RJ conceived, developed, and wrote the bulk of the manuscript. EA, MBe, HB, JJB, JBl, BB, RB, JBo, EB, DC, VC, ML, AC, HC, CCu, ED, RG, GG, VH, SH, RH, SJ, AL-L, NL, AL, GM, JM, AM, EM, MN, SPe, GP, NP, SPo, RP, NR, JS, MTa, HT, MTe, TT, PT, JT, CW, and FW contributed significant ideas and text to the article.

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Detecting Change in the Indonesian Seas

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The Indonesian seas play a fundamental role in the coupled ocean and climate system with the Indonesian Throughflow (ITF) providing the only tropical pathway connecting the global oceans. Pacific warm pool waters passing through the Indonesian seas are cooled and freshened by strong air-sea fluxes and mixing from internal tides to form a unique water mass that can be tracked across the Indian Ocean basin and beyond. The Indonesian seas lie at the climatological center of the atmospheric deep convection associated with the ascending branch of the Walker Circulation. Regional SST variations cause changes in the surface winds that can shift the center of atmospheric deep convection, subsequently altering the precipitation and ocean circulation patterns within the entire Indo-Pacific region. Recent multi-decadal changes in the wind and buoyancy forcing over the tropical Indo-Pacific have directly affected the vertical profile, strength, and the heat and freshwater transports of the ITF. These changes influence the large-scale sea level, SST, precipitation and wind patterns. Observing long-term changes in mass, heat and freshwater within the Indonesian seas is central to understanding the variability and predictability of the global coupled climate system. Although substantial progress has been made over the past decade in measuring and modeling the physical and biogeochemical variability within the Indonesian seas, large uncertainties remain. A comprehensive strategy is needed for measuring the temporal and spatial scales of variability that govern the various water mass transport streams of the ITF, its connection with the circulation and heat and freshwater inventories and associated air-sea fluxes of the regional and global oceans. This white paper puts forward the design of an observational array using multi-platforms combined with high-resolution models aimed at increasing our quantitative understanding of water mass transformation rates and advection within the Indonesian seas and their impacts on the air-sea climate system.

Keywords: Indonesian throughflow, observing system, intraseasonal, ENSO, transport variability, planetary waves

INTRODUCTION

The transfer of water from the Pacific to Indian Ocean via the Indonesian seas, known as the Indonesian Throughflow (ITF), is the only tropical pathway for exchange between ocean basins in the global circulation (**Figure 1**). Pacific waters passing through the Indonesian seas are mixed, cooled and freshened and transformed into unique water masses that can be tracked across the Indian Ocean basin and beyond. The Indonesian seas also lie at the climatological center of the atmospheric deep convection associated with the ascending branch of the Walker Circulation and, as such, play a central role in the climate system. The western node of sea surface temperature (SST) anomalies associated with the El Niño-Southern Oscillation (ENSO) and the eastern node of SST anomalies associated with the Indian Ocean Dipole (IOD) are collocated within the Indonesian seas. The regional SST variations of these major climate oscillations cause changes in the surface winds that may shift the center of atmospheric deep convection, subsequently altering the precipitation and ocean circulation patterns within the entire Indo-Pacific region. Moreover, model studies demonstrate that proper representation of the coupled dynamics between the SST and wind over the Indonesian seas is required for a more realistic simulation of ENSO (Wittenberg et al., 2006; Neale et al., 2008; Annamalai et al., 2010; Koch-Larrouy et al., 2010). Thus, observing the changes in mass, heat and freshwater storage and transfer within the Indonesian seas is central to monitoring and understanding fluctuations in the large-scale ocean and climate systems.

Quantitative knowledge of ITF behavior is of fundamental importance to a wide range of end users including ocean and climate research as well as being of direct societal benefit. Ocean circulation and processes in the Indonesian seas influence not only the local climate but also the global climate through teleconnections with the Pacific and Indian Ocean. Data from the Indonesian seas is therefore of vital importance to regional forecasts and for data assimilation model efforts. Anomalies in the Indo-Pacific SST affect regional rainfall and drought patterns in the many Indian Ocean rim countries that are particularly vulnerable to climate change. Changes in the physical properties of the water are linked to the behavior, migration pattern and the seasonal distribution of the phytoplankton and pelagic fish species that live within the Indonesian seas. The maritime continent is one of the most important reservoirs of marine biodiversity on the planet, which encourages abundant activities in fisheries, aquaculture and tourism. Thus, the necessity of monitoring and forecasting the ITF pathways and variability is significant for the region's people, who depend on the sea for their food and livelihood, and also to help develop management plans to sustain these valuable and limited maritime resources. Understanding the coupled air-sea system in the Indonesian seas is therefore of relevance for regional climate, water resources, and ultimately to the largely agrarian based society through impacts on agriculture, economies, fisheries, and health.

The Ocean Obs '09 (OO'09) white paper (Gordon et al., 2010b) that discussed ITF observations coincided with the release of the first-look papers describing the simultaneous measurements of the velocity and property variability in the major inflow and outflow ITF passages undertaken as part of the International Nusantara Stratification and Transport (INSTANT) program (Gordon et al., 2008; Sprintall et al., 2009). INSTANT measurements provided an estimate of mean ITF transport of 15 Sv into the Indian Ocean, about 30% higher than estimates made from non-simultaneous measurements prior to INSTANT. This first directly observed estimate of the total ITF transport is a definitive benchmark for global and coupled models, and thus has been extensively cited in the ensuing literature. INSTANT revealed many previously undocumented major features of the ITF. In contrast to earlier expectations, INSTANT found that the transport profile in some straits could have a subsurface maximum within the thermocline, with a seasonal phasing and depth level that varied from strait to strait. The vertical profile of the volume transport through each strait sets the heat flux carried by the ITF and cannot be deduced without direct measurement. INSTANT revealed complex variability in the ITF: local and remote wind forcing; tides; intraseasonal to interannual fluctuations; and a plethora of planetary waves that radiate and scatter into the Indonesian seas affecting the currents and mixing. Though capturing this complexity, INSTANT made it obvious that simultaneous measurements in the major inflow and outflow passages are required to accurately depict the full ITF.

While the highly successful INSTANT program delivered a step change in our understanding of the ITF, this program ended more than 10 years ago. In the ensuing years, significant changes have occurred in the Indo-Pacific system, and likely also the ITF, as detected in a few limited direct measurements but mainly inferred from changes downstream in the Indian Ocean. In addition, there are critical phenomena and passages that INSTANT did not resolve well. Consequently, large uncertainties remain in our current understanding of the ITF and its impact on regional SST and the Pacific and Indian Oceans.

In this white paper, we will first present new results (since Gordon et al., 2010b) from recent monitoring programs that have measured aspects of the ITF from its Pacific source, through the Indonesian internal seas, and out through the exit passages into the Indian Ocean. In particular we highlight how recent

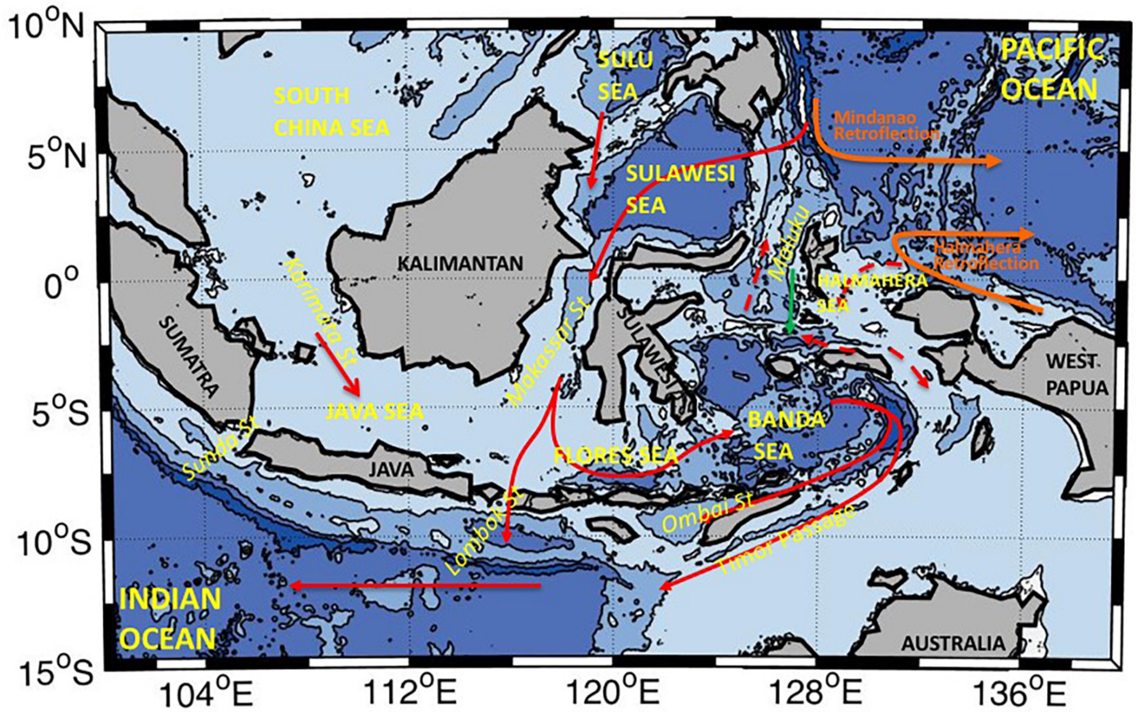

FIGURE 1 | Map of the Maritime Continent, a schematic of the main ITF currents, seas and basins discussed in the text. Upper ocean current pathway is in red, lower pathway in green. Dashed lines indicate uncertain pathways.

changes in the wind and buoyancy forcing over the tropical Indo-Pacific have directly affected the vertical profile, strength, and the heat and freshwater transports of the ITF. We will then discuss the recent direct observations and models that show the tidally driven mixing within the Indonesian seas strongly modifies the temperature and salinity profiles and affects the overall character of the ITF. Finally, anticipated sustained monitoring efforts of the ITF and its associated heat and freshwater fluxes are identified through examination of the strengths and challenges in developing an ITF observing system, taking advantage of emerging new technologies. We conclude by proposing a strategy for an integrated observing array that exploits multiple platforms. As such, this paper connects to the OO'19 vital conference theme of *Climate Variability and Change* and addresses the underlying theme of *Observing Technologies and Networks*.

CURRENT STATUS OF THE OBSERVING SYSTEM IN THE INDONESIAN SEAS

Introduction

The Indonesian seas provide a complex gateway from the Pacific to Indian Ocean via a myriad of narrow channels connecting seas and basins of varying depths and sizes (**Figure 1**). The primary inflow channeling the tropical North Pacific water through the Indonesian seas is within Makassar Strait, carrying about ~80% (12–13 Sv) of the total ITF (Susanto and Gordon, 2005; Gordon et al., 2010a). The remainder of the ITF enters via the more porous eastern passages of the Indonesian seas via the Maluku Sea, with a South Pacific contribution mostly entering through the Halmahera Sea, as well as a density-driven overflow through Lifamatola Passage that ventilates the deeper layers of the Banda Sea. Smaller amounts (1-2 Sv) are injected by direct inflow from the South China Sea (SCS) via Karimata Strait (Fang et al., 2010; Susanto et al., 2013) and through the Sibutu Passage into the Sulawesi Sea that draws water from the Sulu Sea derived from the SCS (Gordon et al., 2012). The ITF exits into the Indian Ocean primarily through gaps along the Nusa Tengarra island chain, but mostly through Lombok Strait, Ombai Strait and Timor Passage. There is likely a small amount of exchange occurring across the shallow but broad Australian Northwest Shelf. Downstream in the tropical Indian Ocean, the ITF sustains a narrow relatively cool, low salinity streak in the upper thermocline (Gordon et al., 1997) and a distinctly different core of high silicate, low salinity intermediate ITF waters (Talley and Sprintall, 2005).

Trade winds over the western Pacific and the Australian – Indonesian monsoon winds together maintain a pressure difference between the Pacific and Indian Ocean, that generally regulates the mean ITF (Wyrtki, 1987). The transient component of the winds over the equatorial Pacific and Indian Oceans affect the inter-basin pressure difference through the formation of planetary waves and hence contribute to the variability of the ITF on a broad range of timescales. Annual equatorial Rossby waves originating in the eastern Pacific Ocean propagate westward across the tropical Pacific Ocean and modulate sea surface height over the western boundary of the Pacific, that in turn contribute to seasonal variations of the interocean pressure gradient and subsequently the ITF (Potemra, 1999). The equatorial Rossby and Kelvin waves respectively, impinge upon the western boundary of the Pacific and the eastern boundary of the Indian Ocean (the "Wyrtki Jet"; Wyrtki, 1973), forming coastal Kelvin waves that penetrate into the Indonesian seas and modulate the ITF (Wijffels and Meyers, 2004). Over the equatorial Indian Ocean, strong wind transitions force upwelling and downwelling equatorial Kelvin waves on intraseasonal, semi-annual and interannual time scales that dictate variations of the ITF (Sprintall et al., 2000; Pujiana et al., 2009, 2013; Drushka et al., 2010; Yuan et al., 2011, 2013; Shinoda et al., 2012).

The ITF also experiences substantial interannual variations, influenced by the Indian and Pacific wind forcing. It is expected that when the Pacific wind stress is weak or reversed during El Niño conditions, that this would lead to a weaker ITF, and vice-versa under La Niña conditions. However, in reality the ENSO relationship to transport is not clear cut in all the passages. Part of the complication lies because no two ENSO events are the same, and part also lies with whether the ENSO is concurrent (or not) with IOD events that also have a strong impact on the ITF transport. It is critical to understand climate variability at interannual time scales since they can mask and complicate interpretation of the long-term trends and decadal variability. The interannual to decadal behavior of the ITF and how well this is simulated in seasonal to climate models remains a major research challenge.

Since OO'09, we have uncovered fresh knowledge about the variability of the ITF and the nature of the processes that cause that variability. The *in situ* observations maintained over the past decade in the Indonesian seas that have contributed to this understanding are listed in the **Supplementary Table 1**. The observational evidence supported by models show that recent changes in the Indo-Pacific wind and buoyancy forcing have dramatically affected the vertical profile and flow through the Indonesian seas. In addition, recent studies focused on intraseasonal variability in the Indonesian seas have intensified, motivated in part by the international Years of the Maritime Continent (YMC) project. Finally, we discuss decadal and longer term variability that while mostly observed in the Indian Ocean, can be attributed to long-term ITF influence. This section highlights these and other new findings.

Variability in Observed Pathways of the ITF

Makassar Strait

There are now ~13.5 years of measurements of the Makassar Strait throughflow within the Labani Channel constriction (sill depth ~680 m) (**Figure 2A**) constituting the longest time series in any stream of the ITF (Gordon et al., 2019). The complete record attests to the power and insight afforded by extended time series. The growth of the time series has enabled a more quantitative detection of the variability over a broad range of time scales.

An unexpected attribute of the Makassar Strait throughflow is that the strongest southward flow is not within the warm sea surface layer but rather within the cooler thermocline (**Figure 2**). The likely cause of the subsurface velocity maximum is the injection of buoyant, low salinity surface water drawn into Makassar Strait from the SCS and Java Sea (Gordon et al., 2003, 2012; Tozuka et al., 2007, 2009; Fang et al., 2010; Susanto et al., 2010, 2013) as well as from Sunda Strait (Susanto et al., 2016). This buoyant layer creates a "freshwater plug" that inhibits the inflow of tropical Pacific surface water from the Mindanao Current. The SCS effect in the upper ~100 m is strongest during boreal winter and extends into spring, albeit with distinct interannual variability. Stronger southward flow within Makassar Strait occurs in the upper 300 m during the boreal summer.

The Madden-Julian Oscillation (MJO) and shear instability-generated eddies together dictate intraseasonal variations in the upper 200 m of the Makassar Strait throughflow (Pujiana et al., 2012; Napitu, 2017; Napitu et al., 2019). The MJO is strongest during boreal winter monsoon across the Indonesian seas (Napitu et al., 2015). During boreal winter the MJO is thought to weaken the Pacific to Indian Ocean pressure gradient and so increase the northward (toward the Pacific Ocean) momentum transfer from wind stress. In turn, this induces monthly pulses of northward along-strait flow in the surface layer in Makassar Strait resulting in a substantial reduction of the ITF transport in the upper layer of Makassar Strait (Napitu, 2017, Napitu et al., 2019). Increased turbulent stress at the base of the upper layer also acts to decelerate the anomalous ITF transport toward the Pacific Ocean during MJO events. This contributes to the seasonal reduction of the southward throughflow (Napitu, 2017; Napitu et al., 2019). Indian Ocean Kelvin waves are identifiable from the observations as northward flows beneath 200 m (**Figure 2**), acting to regulate the intraseasonal and semi-annual (May and November) variability in Makassar Strait (Pujiana et al., 2009, 2013; Susanto et al., 2012).

Interannual variability in Makassar Strait scales roughly to ENSO, with reduced transport and a deeper and weaker maximum velocity during El Niño and stronger southward flow with shallower stronger maximum velocity during La Niña (**Figure 3**; Gordon et al., 2010b, 2012; Susanto et al., 2012). The 13-year time series shows a prolonged shoaling and strengthening of the ITF since 2007 (**Figure 2**; Gordon et al., 2012). The thermocline velocity maximum shifted from 140 to 70 m depth and velocity increased from 70 to 90 cm/s. Models suggest that this might be related to ENSO events that control the presence of buoyant freshwater pools in the inflow region and so act to modulate the surface layer contribution to the Makassar throughflow via the "freshwater plug" (Gordon et al., 2012).

Since 2016 the deep layer (300–760 m) southward transport has increased, almost doubling to ~7.5 Sv (**Figure 4**). From late 2016 into early 2017 the transport above 300 m and below 300 m are about equal, whereas there is usually a ratio of 2:1. In early 2017 the total Makassar transport reached an 'historical' high of over 20 Sv. A particularly strong surface layer reversal is observed in the winters of 2014/15 and 2016/17 – the latter is the strongest winter reversal revealed in the Makassar time series (Pujiana et al., 2019). In June/July 2016 there is a marked relaxation of the southward flow within the thermocline, dividing the summer maximum into two separate features. During this event the ITF

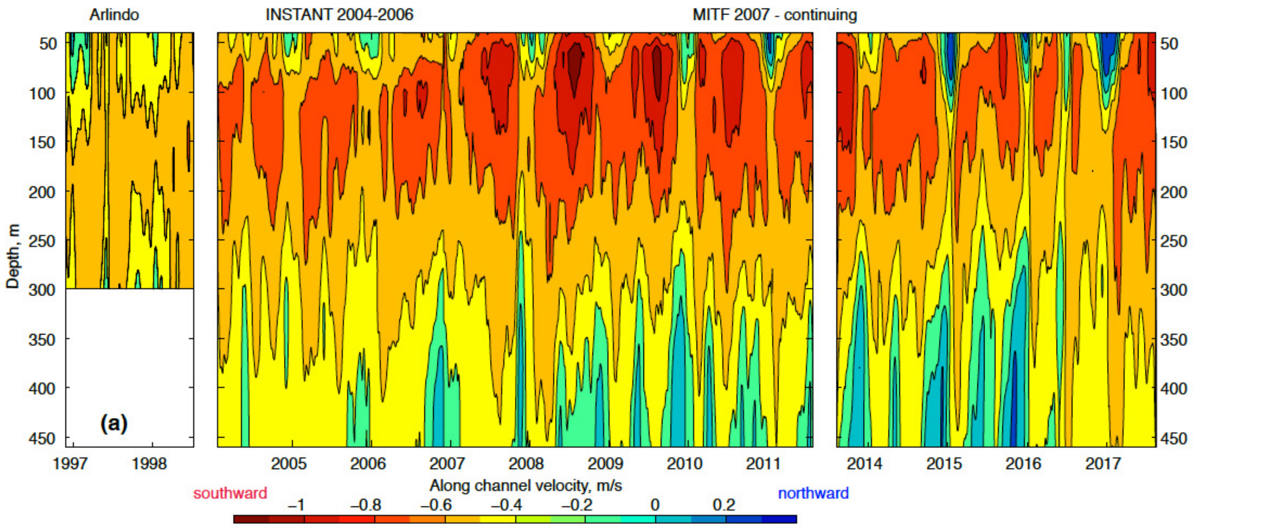

FIGURE 2 | Time series of currents (m/s; 30-day running average), from ~50 to 450 m depth, along the axis of Labani Channel of Makassar Strait. Red colors are toward the south (Indian Ocean), blue colors to the north (Figure from Gordon et al., 2019).

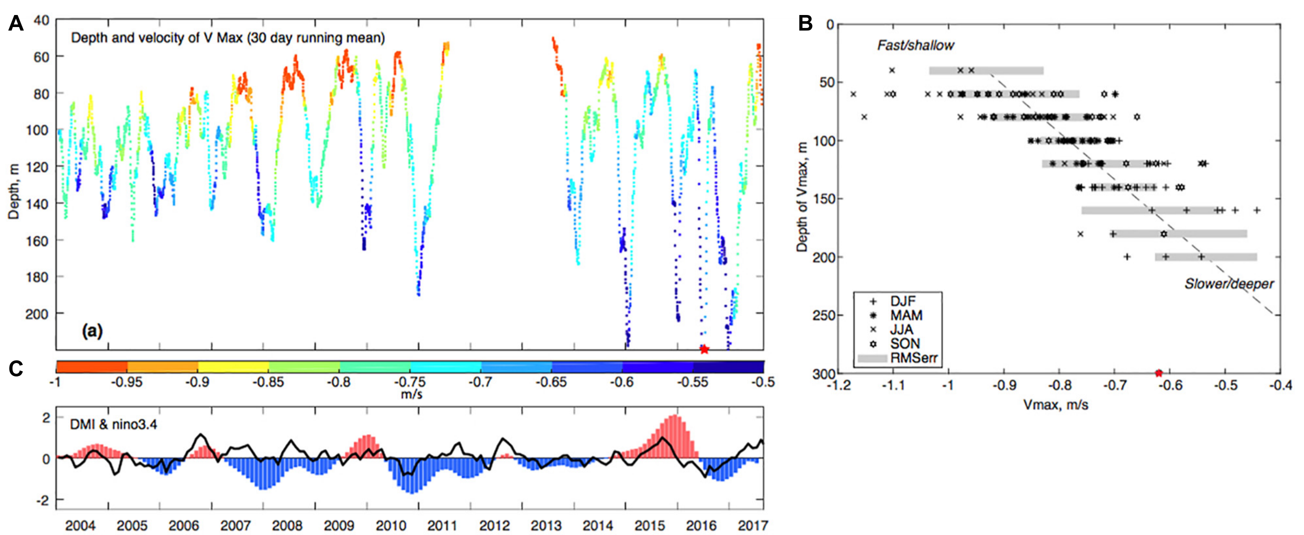

FIGURE 3 | (A) Time series of depth of the velocity maximum (Vmax) from the mooring within Labani Channel of Makassar Strait, color coded by speed (m/s). An anomalous deep Vmax occurred in June/July 2016, which is likely the imprint of a strong Kelvin Wave intrusion from the Indian Ocean. **(B)** The IOD (black line) and Nino3.4 Index (blue: la Niña; red: el Niño) over the same period as the mooring deployment. **(C)** Scatter plot of Depth of Vmax versus Vmax stratified by season (Figure from Gordon et al., 2019).

is northward, a condition that in prior years was seen only in the boreal winter. Anomalously strong boreal summer MJO events may be the cause of this unusual relaxation of the ITF in the upper layer in June 2016, while the flow in the lower thermocline is impacted by an anomalously strong Wyrtki-jet in the Indian Ocean that forced a northward propagating Kelvin wave through Makassar Strait (Pujiana et al., 2019).

The Makassar southward heat flux anomaly (relative to a mean heat flux referenced to 0°C; Gruenburg and Gordon, 2018) increased rapidly from 2006 to 2008 with a peak of 0.13 PW in 2008 and 2009. Makassar heat flux anomaly then slowly decreased to a minimum of −0.22 PW during 2015 before climbing again in recent years. The heat content anomaly in the eastern tropical Indian Ocean, determined from Argo profiles, follows a similar pattern to the Makassar heat flux anomaly with a lag of 2 to 3 years.

Eastern Passages

The circulation at the entrance of the Indonesian seas is characterized by two western boundary currents, the North

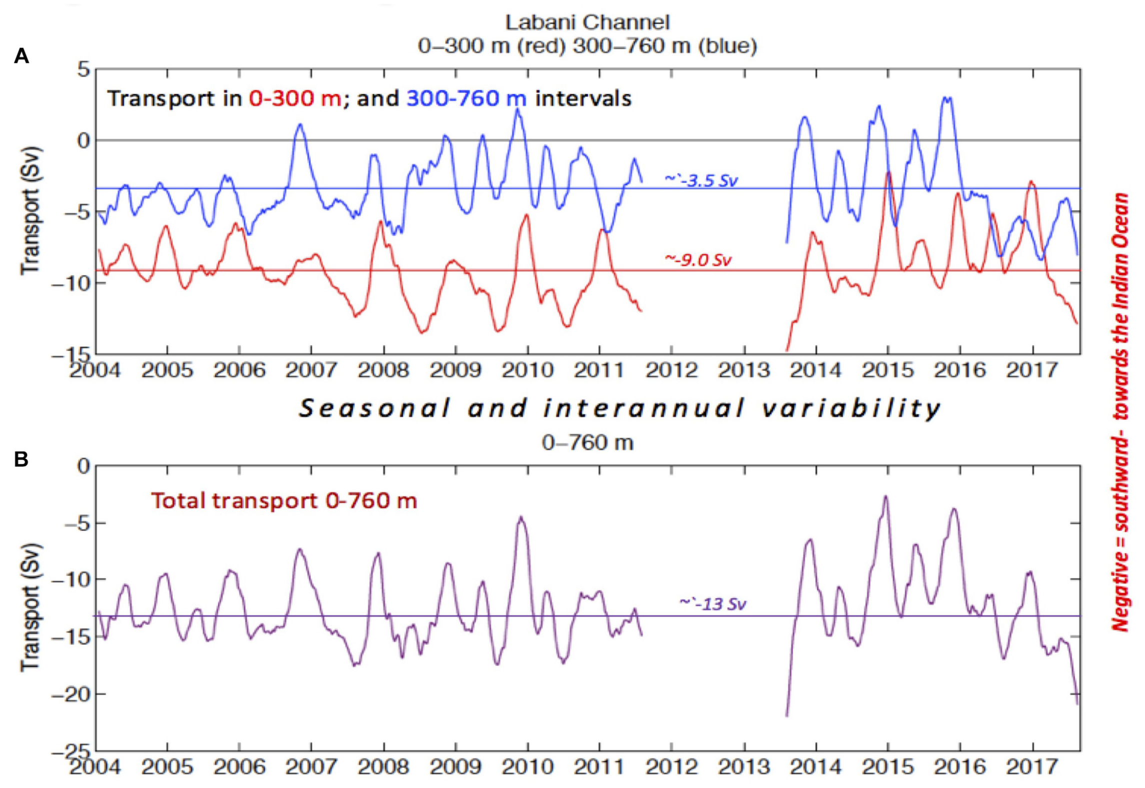

FIGURE 4 | (A) Volume transport in Sv (Sv, Sverdrup = 10^6 m^3/sec) for the 0–300 m interval (red) and 300–760 m interval (blue) and **(B)** the total transport 0–760 m (purple). Negative flow is southward toward the Indian Ocean (Figure from Gordon et al., 2019).

Pacific Mindanao Current and the South Pacific New Guinea Coastal Current/Undercurrent system. These two low latitude western boundary currents collide to generate the westward flowing ITF, and the Mindanao and Halmahera retroflections that feed into the eastward flowing North Equatorial Countercurrent, as well as feeding into the Equatorial Undercurrent at depth. The retroflections and the presence of eddies at the Pacific entrance induce hysteresis effects and non-linear bifurcations that are thought to impact the transport, water properties, thermocline and sea level variability within the Indonesian seas (Kuehl and Sheremet, 2009; Yuan and Wang, 2011; Wang and Yuan, 2012, 2014).

The ITF variability in the eastern passages is poorly understood. The upper level transport through Lifamatola Passage and the other northeastern passages was not fully resolved during INSTANT. Only the deep part of Lifamatola Passage was monitored, with about 2.5 Sv found to enter the Indonesian seas below 1250 m (van Aken et al., 2009). However, since INSTANT, moorings have been deployed within the inflow pathways over the Sangihe Ridge, the Muluku Channel and the Halmahera Strait (**Figure 1**).

The upper 300 m Maluku Channel transport measured from December 2012 through November 2016 has a mean transport of 1.04 -1.31 Sv northward (**Figure 5**), although there is significant intraseasonal-to-interannual variability of over 14 Sv (Yuan et al., 2018). In particular, a southward change of over 3.5 Sv occurred in the spring of 2014. A high-resolution numerical simulation suggests that the variations of the Maluku Channel currents are associated with the shifting of the Mindanao Current retroflection. The spring 2014 change was coincident with a choked state of the Mindanao Current at the entrance to the Indonesian seas, which is different from the more eastward climatological retroflection typical of boreal fall-winter. The shifting of the Mindanao Current elevated the sea level at the entrance of the Indonesian seas driving the anomalous transport through the Maluku Channel. The results suggest the importance of the western boundary current non-linearity in driving the transport variability of the ITF.

The transport through the eastern passage of Halmahera Strait is thought to be small but represents an injection of saltier South Pacific water that is important for water mass transformation in the Indonesian seas (Cresswell and Luick, 2001; Koch-Larrouy et al., 2007). The bathymetry of the Halmahera Sea is convoluted with numerous small basins and shallow sills confounding attempts to obtain meaningful transport estimates. Numerous attempts have been made to determine transport from single point moorings (Cresswell and Luick, 2001; Koch-Larrouy, personal communication; Yuan, personal communication) with estimates of the mean transport across the Halmahera Strait ranging from −1.5 Sv (westward) from June 1993 to June 1994 (Cresswell and Luick, 2001) to −2.4 Sv from November 2015 to October 2017 (Yuan, personal communication).

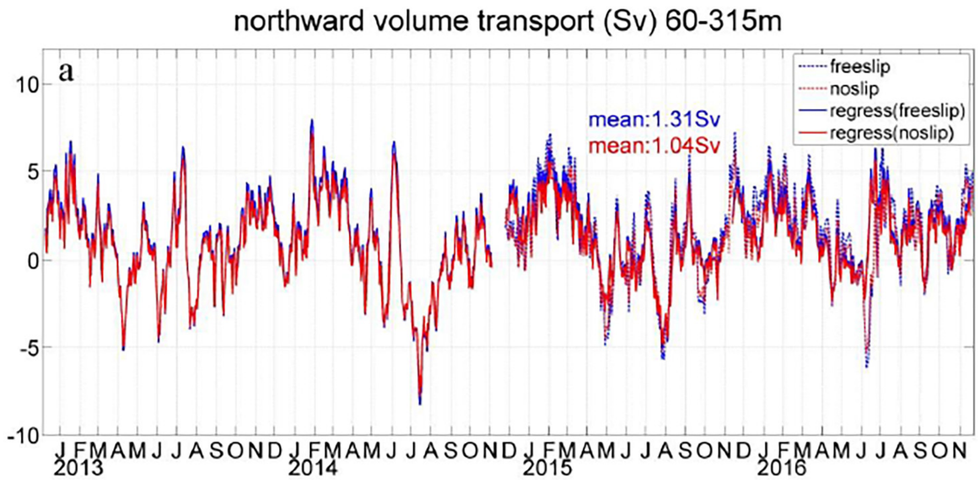

FIGURE 5 | Time series of the Maluku Channel transport (Sv) between 60 and 315 m from three ADCP moorings deployed during 2015–2016 assuming free-slip (red dotted) and nonslip (blue dotted) conditions at the coasts, respectively. Solid blue and red curves are a regression model using the transport and the meridional velocity at the middle mooring that is then used to estimate the transports (from the middle mooring velocity) during 2012–2014 (Figure from Yuan et al., 2018).

Western Pathways From the South China Sea

The western route of ITF pathways via the Karimata Strait plays an important role in controlling the freshwater flux from the SCS into the Indonesian seas, impacting the ITF stratification (Tozuka et al., 2007, 2009; Susanto et al., 2010, 2013; Wang et al., 2019; Wei et al., 2019). In the main, the variability of the ITF transport is out-of-phase with the SCS Throughflow (Liu et al., 2006) that is well explained by the Island Rule theory (Qu et al., 2005; Wang et al., 2006). However, the SCS inflow contribution can vary from tidal to interannual time scales (Fang et al., 2010; Susanto et al., 2013; Wei et al., 2015). The inflow is influenced by seasonal reversal monsoon winds with stronger southward flow toward the Java Sea (−2.7 ± 1.1 Sv) during the boreal winter monsoon and lesser flow toward the SCS (1.2 ± 0.6 Sv) during the boreal summer monsoon (Fang et al., 2005, 2010; Susanto et al., 2010, 2013; Wang et al., 2019; Wei et al., 2019).

The Sunda Strait flow is northward toward the Java Sea during boreal winter monsoon (0.24 ± 0.1 Sv) and southward (–0.83 ± 0.2 Sv) toward the Indian Ocean during the boreal summer monsoon (Susanto et al., 2016). The Sunda Strait is the first gap of the pathway for coastally trapped Kelvin waves from the equatorial Indian Ocean. Intraseasonal inflows associated with Kelvin waves observed in Sunda Strait (Li S. et al., 2017) affected chlorophyll-a concentrations: higher levels were observed during outflow to the Indian Ocean and lower levels during inflow to the Java Sea (Xu et al., 2018). Thus, although the SCS inflow via the Karimata and Sunda Straits is smaller than the Makassar Strait inflow, both streams have a significant impact on the ITF stratification, freshwater flux and ecosystems within the Java Sea.

Outflow Passages

INSTANT found a total mean ITF transport from 2004 to 2006 of −15 Sv toward the Indian Ocean through the three major outflow passage comprised of −2.6 Sv in Lombok Strait, −4.9 Sv in Ombai Strait and −7.5 Sv in Timor Passage (Sprintall et al., 2009). The combined transport in Timor Passage and Ombai Strait is >80% of the full-depth ITF transport, although Lombok Strait transport most resembles the variability of the total transport. The vertical transport structure in both Timor Passage and Lombok Strait are primarily surface intensified, although both flows have a weak subsurface maximum at 50–60 m. The Ombai Strait transport profile features both a surface maximum and an equally strong subsurface maximum near 180 m depth. Due to its shallow sill, Lombok carries the warmest waters (21.5°C), Timor the next warmest (17.8°C), and Ombai the coldest (15.2°C) because of the subsurface velocity maximum.

As for the inflow passages, variability in the outflow is found over all time scales. The ITF outflow is strongly influenced by the Asian-Australian Monsoon. During the transition between the monsoons the reversal of the wind forcing over the Indo-Pacific results in a large seasonal and semiannual variation in the outflow transport and hence also in the transport weighted temperature and heat flux (Sprintall et al., 2009) as well as the nutrient flux (Ayers et al., 2014). The intraseasonal MJO variability affects the evolution of seasonal signals through the propagation of upwelling and downwelling Kelvin waves from the Indian Ocean (Drushka et al., 2010).

The Australian Integrated Marine Observing System (IMOS) deployed moorings in the Ombai Strait and Timor Passage between 2011 and 2015. The Ombai mooring occupied the same location as the INSTANT southern mooring in Ombai, however, the moorings in Timor Passage were located at the eastern edge of the passage and the array extended across the broad continental shelf north of Australia. The moorings in the Timor Passage and over the continental shelf underlie an altimeter ground track. Comparison of the Ombai Strait interannual transport variability and its relationship to the winds is quite different between the INSTANT (2004–2006) and IMOS ITF period (2011–2015) (**Figure 6**). The 7-year time series shows that while some of the transport peaks align with the wind divergence (La Niña/negative IOD), others do not. In addition, the upper (0–150 m) and deeper

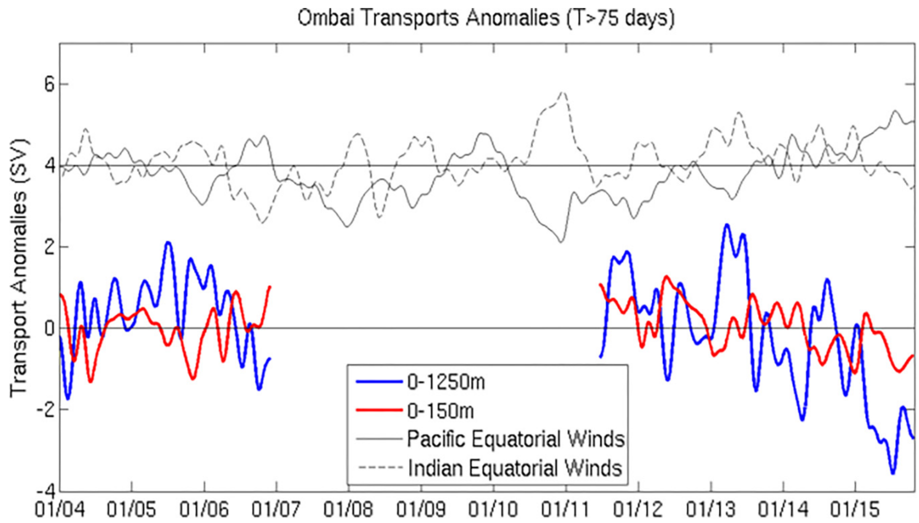

FIGURE 6 | Interannual (T > 75 days) time series of Ombai Strait transport anomalies from INSTANT (2004–2006) and IMOS ITF (2011–2015) for depth ranges 0–150 m (blue) and 0–1250 m (red). Also shown are the normalized zonal equatorial Pacific (solid) and Indian (dashed) Ocean winds from 2004 to 2015. Negative winds anomalies reflect stronger westerly trades winds over the equatorial region (Data from Wijffels et al., 2018).

(0–1250 m) transport anomalies are often out of phase. It is not yet clear what processes might drive these contrasting responses.

The net transport in the Timor Passage/Continental Shelf is smaller than found during the INSTANT program. The flow in the Timor passage at the IMOS mooring site is broader and more southern intensified than the narrower strait-centered jet measured by INSTANT at the western end of the Passage. While Ombai is strongly semi-annual at all depths, Timor Passage varies semi-annually only at depth (**Figure 7**), with annual variations dominating the stronger upper ocean component.

Using a proxy time series developed from INSTANT transport data in the outflow passages and altimetry data, Sprintall and Revelard (2014) found the partitioning of the total ITF transport through each of the major outflow passage varies according to the phase of the IOD or ENSO. In general, Pacific ENSO variability is strongest in Timor Passage, most likely through the influence of planetary waves transmitted from the Pacific along the Northwest Australian shelf pathway. Somewhat surprisingly, concurrent El Niño and positive IOD episodes consistently show contradictory results from those composites constructed for purely El Niño episodes, particularly in Lombok and Ombai Straits, but also at depth in Timor Passage. This suggests that Indian Ocean dynamics likely win out over Pacific Ocean dynamics in gating the transport through the outflow passages during concurrent ENSO and IOD events.

The ITF in the South-Eastern Indian Ocean

One of the longest running transport measurements in the Indo-Pacific region comes from a frequently repeated XBT section between Western Australia and Java – the IX1 line. This remarkable data set enables a monthly ocean geostrophic estimate of the upper ITF (0–700 m) to be made extending back 35 years since 1983.

On interannual and longer time scales, remotely driven low frequency Pacific wind energy penetrates into the Indonesian seas and southward along the Western Australian coast (Pariwono, 1986; Wijffels and Meyers, 2004; McClean et al., 2005) and modulates both sea level and thermocline depth with the ENSO variability (Clarke and Liu, 1994). Wind-driven planetary long waves excited along the equatorial and coastal wave guides in the Indian Ocean also play a role in modulating the interocean exchange on intraseasonal through to interannual timescales. Wijffels and Meyers (2004) showed that about 60–90% of sea level variability and 70% of thermocline temperature variability within the Indonesian seas and geostrophic transport along the IX1 section can be understood in terms of free Kelvin and Rossby waves.

The multi-decadal IX1 time series has formed the observational basis of many recent analyses probing long-term changes in the Indo-Pacific circulation system. Interannual and multi-year variations of the ITF volume and heat transport may provide feedbacks to the climate variability in the Indo-Pacific. For example, based on IX1 XBT data analysis, the often co-occurring positive IOD (negative IOD) with El Niño (La Niña) was found to actually counter the direct ENSO effect during the developing phase of ENSO, resulting in a delayed ITF transport response to ENSO variability (**Figure 8A**; Liu et al., 2015; Feng et al., 2018). After the 2015/2016 El Niño, there was an unprecedented reduction of the ITF volume and heat transport, which is linked to a documented intensified warming and associated rising sea levels in the Indian Ocean over the last decade (Han et al., 2014). This may partly explain the weak and short lived La Niña conditions in 2016/2017 (Mayer et al., 2018).

The ITF outflow into the south-eastern Indian Ocean is also influenced by upwelling along the coast south of Java that occurs seasonally and is strengthened interannually as part of the IOD.

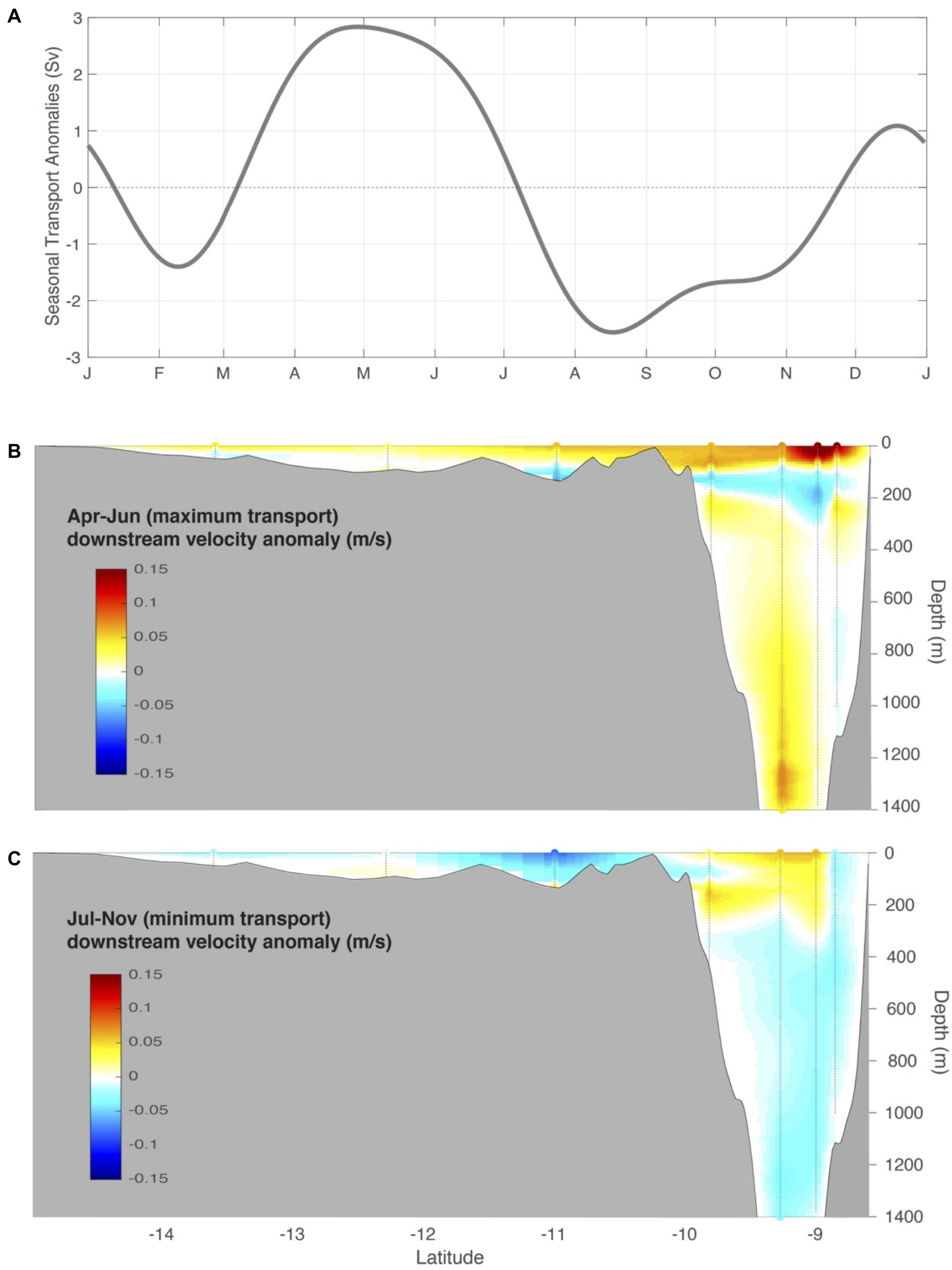

FIGURE 7 | Timor Passage and extension to northern Australian continental shelf IMOS moorings (2011–2015) **(A)** seasonal transport (Sv) anomaly, mean vertical velocity (m/s) section for **(B)** April-June and **(C)** July–November. April–June corresponds to maximum net transport and July–November to minimum net transport.

The positive IOD can lift the thermocline depth off the Sumatra-Java coast in response to the enhanced upwelling (Feng and Meyers, 2003), and thus can induce a stronger ITF transport. Negative IOD would induce a weakened ITF transport anomaly. Together the upwelling and the ITF water supply the South Equatorial Current (SEC) within the Indian Ocean (Wyrtki, 1962; Qu and Meyers, 2005). Indeed, the ITF/SEC mass transport could also be a trigger for the upwelling south of Java on both seasonal (Purba, 2007; Valsala et al., 2011; Kuswardani and Qiao, 2014) and IOD time scales (Delman et al., 2016; Delman et al., 2018).

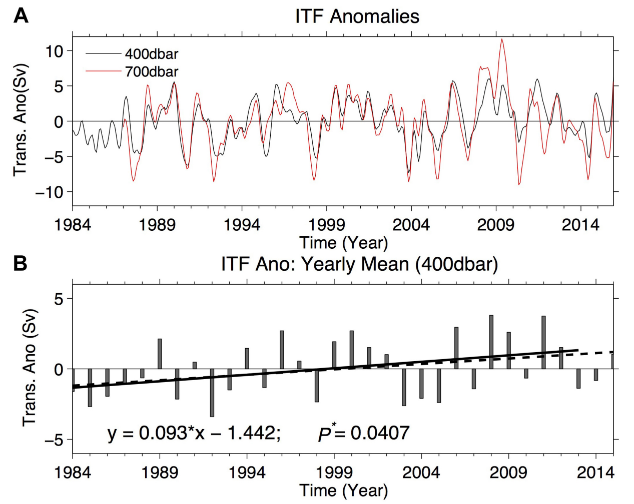

FIGURE 8 | The ITF geostrophic transport anomalies estimated from IX1 XBT data in the southeast Indian Ocean. **(A)** A monthly time series of the ITF transport anomalies estimated by IX1 XBT temperature records and monthly T-S relationship with reference depths of 400 m (black line) and 700 m (red line) from January 1984 to December 2015. Negative is toward the Indian Ocean (i.e., stronger ITF). **(B)** Annual mean ITF transport anomalies with a reference depth of 400 db (bars) and their linear trends (lines) during 1984–2013 and during 1984–2015 (Figure from Feng et al., 2018. Permission obtained from author).

Intraseasonal Variability Over the Maritime Continent

Despite substantial recent progress over the past decade toward understanding the generation mechanism of the MJO in the Indian Ocean (e.g., Yoneyama et al., 2013; Moum et al., 2014; Pujiana et al., 2018), the MJO dynamics are still not fully understood, particularly those controlling the MJO behavior over the Indonesian seas. The mountainous Sumatra island, the westernmost island of the Indonesian archipelago, appears to exert a blocking effect on the eastward propagation of the MJO (Inness and Slingo, 2006). Weakened activities of the MJO over the Indonesian maritime continent have been attributed to competing interactions between diurnal precipitation over the Indonesian islands and the larger-scale MJO convective system (Peatman et al., 2014; Baranowski et al., 2016; Hagos et al., 2016). While land-air interactions have been suggested as the main mechanism responsible for the eastward propagation of the MJO over the maritime continent, the roles of air-sea interactions have been less explored. Improving our understanding on the underlying processes attributed to the MJO propagation, specifically the air-sea-land response to MJO forcing that is unique to the maritime continent, is critical because most rainfall within the Indonesian region is associated with MJO events. Understanding the variability on this time scale has received much attention since OO'09 as it is a principal focus of the YMC to be undertaken in 2018–2020.

Over the broader Indo-Pacific region, MJO-driven heat fluxes govern the heat content variability within the oceanic mixed layer (Drushka et al., 2012). Within the Indonesian seas, the MJO surface heat fluxes account for a significant fraction of intraseasonal SST variances, with the strongest imprint observed in the Banda and Timor Seas (Napitu et al., 2015). Intraseasonal SST response to the MJO exhibits seasonal variation (strong during December-February and weak during June-August) and is dependent upon thickness of the surface mixed layer (Napitu et al., 2015). In addition, intraseasonal SST variance in the Banda and Timor Seas is also sensitive to thermocline depth. Deep thermoclines during December-February and La Niña (Gordon and Susanto, 2001) may decouple the surface mixed layer from the thermocline, making conditions more favorable for surface fluxes to regulate the rate of change of the mixed layer heat content. Shallow thermoclines during June-August and El Niño may intensify heat transfer between the surface mixed layer and the thermocline, elevating the role of ocean processes to govern the mixed layer heat content. Contributions from other oceanic processes that may govern SST response to the MJO, such as turbulent mixing, remain largely unknown.

The Indonesian seas not only respond to the MJO but may influence the evolution of the MJO while it traverses over the maritime continent. Only about 60% of the MJO events from the Indian Ocean appear to propagate over the maritime continent into the western Pacific (Napitu, 2017). Increased moisture content in the atmospheric boundary layer over the maritime continent, due to the warmer SST in the Indonesian seas, likely plays an important role in determining the MJO eastward propagation over the maritime continent to the western Pacific. Locally increased low-level specific humidity could strengthen the zonal gradient of moist static energy between the Indian Ocean and the Pacific Ocean, a key condition allowing MJO propagation over the maritime continent. An increased diurnal cycle amplitude explained the warmer SST observed during the suppressed phase of the MJO (Napitu, 2017). On interannual time scales, eastward propagation of MJO events occur more frequently during La Niña years than during El Niño years. The thermocline tends to be deeper during La Niña, thus inhibiting access of the cooler waters that would reduce SST and attenuate the MJO event.

Decadal and Longer Time Scale Changes

Because there is a lack of decadal modes of climate variability in the Indian Ocean (Han et al., 2014), decadal variations of the ITF transport are mainly associated with the decadal climate modes in the tropical Pacific, such as the Pacific Decadal Oscillation (PDO; Zhuang et al., 2013). On decadal and longer time scales, the circulation in the western equatorial Pacific Ocean is subject to the influence of the PDO that strengthens (weakens) the tropical Pacific trade winds during negative (positive) phases. The PDO is predictable if the meridional transport of the tropical gyre is used as a precursor (Zhou et al., 2018). The PDO pattern is believed to relay the corresponding anomalies into the marginal seas of the western Pacific Ocean, including the Indonesian seas, via westward propagating baroclinic Rossby waves (Lee and McPhaden, 2008; Trenary and Han, 2013; Dong and McPhaden, 2016). The changes ultimately impact the south Indian Ocean subsurface temperature and heat content variations (Ummenhofer et al., 2017; Zhou et al., 2017).

Decadal modification of the Indo-Pacific atmospheric Walker Circulation (Vecchi et al., 2006; England et al., 2014) has directly influenced the strength of the ITF (Alory et al., 2007; Lee and McPhaden, 2008; Feng et al., 2011; Merrifield and Maltrud, 2011; Sprintall and Revelard, 2014; Hu et al., 2015; Liu et al., 2015; Mayer et al., 2018), as well as the heat (Alory et al., 2007; Schwarzkopf and Böning, 2011; Lee et al., 2015; Liu et al., 2015; Nieves et al., 2015) and freshwater (Phillips et al., 2005; Vargas-Hernandez et al., 2015; Du et al., 2015; Hu and Sprintall, 2016, 2017) that has been redistributed from the neighboring Pacific through the Indonesian archipelago into the Indian Ocean.

Our first inkling that the PDO phases might impact ITF variability came when observational studies supported by model experiments found that the PDO-related climatic shift of 1976/77, associated with weakening of the easterly trade winds, led to shoaling thermocline anomalies in the western Pacific causing a decrease of the ITF into the Indian Ocean (Vecchi et al., 2006; Alory et al., 2007; Wainwright et al., 2008). Temperature records along IX1 after the mid-1970s to 1990s compared with historical observations from the 1950s to 1960s showed subsurface cooling anomalies corresponding to a weakened ITF geostrophic transport compared with the earlier decades (Alory et al., 2007; Wainwright et al., 2008; Liu et al., 2010). The response was similar to that which occurs during ENSO induced wind shifts (Wijffels and Meyers, 2004).

During the 2000s, the PDO transitioned toward its negative (La Niña like) phase with enhanced Pacific trade winds (Kosaka and Xie, 2013; England et al., 2014) that caused a dramatic heat increase in the Indian Ocean via the ITF, especially in the main thermocline (100–350 m) and in the southeast Indian Ocean (Feng et al., 2011; Lee et al., 2015; Nieves et al., 2015; Dong and McPhaden, 2016; Liu et al., 2016; Cheng et al., 2017; Li Y. et al., 2017; Ummenhofer et al., 2017; Zhou et al., 2017). The strengthening trend of the ITF geostrophic transport across the IX1 XBT section is about 1 Sv every 10 years over the period 1984–2013 (Liu et al., 2015; Feng et al., 2018), although the trend may start to reverse due to the influence of the most recent El Niño events in 2014–2016 (**Figure 8**). This is consistent with a multi-decadal timeseries of 0–300 m Makassar Throughflow, reconstructed from NCEP reanalysis wind data and Makassar Strait transport, suggesting that the Makassar throughflow decreased from 1948 to 1995, increased after 1995, and decreased after 2013 (Li et al., 2018). Over longer time scales, a coral record suggested that the PDO significantly impacted the Indo-Pacific coupling (Crueger et al., 2009), influencing the ITF strength over the past 200 years that consequently played an important role in modulating the warming rate in the Indo-Pacific basins (Hennekam et al., 2018).

Heat redistribution in the upper layer through the ITF has also been closely tied to the surface warming hiatus from the mid 1990s through mid-2000s, leading to heat content changes in the Pacific and Indian Oceans. During the hiatus period, the enhanced ITF heat transport compensated the enhanced heat uptake by the Pacific Ocean (Lee et al., 2015; Nieves et al., 2015; Dong and McPhaden, 2016; Liu et al., 2016) and led to an accelerated warming in the south Indian Ocean. These changes are evident in the observations, model simulations and reanalysis products from the Indian Ocean. At present there are relatively few direct time series records available in the Indonesian seas that might be used to directly corroborate the link to corresponding changes in the ITF profile.

In addition to sea temperature changes, decadal sea surface salinity trends are also evident in the Indo-Pacific region (Du et al., 2015), and salinity variability is known to play a role in regulating the ITF transport (Gordon et al., 2003; Andersson and Stigebrandt, 2005; Feng et al., 2015; Hu and Sprintall, 2016, 2017; Newton, 2018). The advection of freshwater from the Indonesian seas results in an average freshening of 0.2 psu in the Indo-Australian basin during strong La Niña events (Phillips et al., 2005; Zhang et al., 2016). Andersson and Stigebrandt (2005) proposed that buoyancy forcing associated with freshwater gain and vertical mixing in the northern and equatorial western Pacific is an important factor to determine the pressure gradient between the ocean basins that regulates the long-term ITF transport from the Pacific to the Indian Ocean (Wyrtki, 1987). Hu and Sprintall (2016) found that about 36% of the interannual ITF transport is attributable to the halosteric contribution. Strengthening of the ITF transport in the 2000s, and the significant increase in freshwater input over the Indonesian seas, contributed to a subsequent warming and freshening of the eastern Indian Ocean (Hu and Sprintall, 2017).

In the future, climate models consistently project a substantial decrease in the ITF transport in response to enhanced greenhouse warming. A multi-model mean reduction of 3.4 Sv is predicted by the end of the century, corresponding to >20% of the multi-model mean ITF transport of 15 Sv (Hu et al., 2015; Sen Gupta et al., 2016). The declining trend of the ITF in the future climate scenarios appears to be associated with a weakening trend of deep water formation in the Southern Ocean and a slowdown of upwelling in the deep Pacific Ocean (Sen Gupta et al., 2016). Using an eddy-rich (10 km) downscaled near-global ocean model captures a similar weakening of the ITF that is mainly attributed to the slowdown of the deep upwelling in the Pacific basin in the future (Feng et al., 2017). This implies that the deep contribution to the ITF will be weaker in a future warm climate, influenced also by the stronger near-surface water column stratification and a reduction of deep water formation rate.

MIXING OBSERVATIONS AND TIDAL MODELING: SIGNIFICANCE TO WATER MASS FORMATION AND CLIMATE

Introduction

Perhaps one of the most consequential outcomes of recent research within the Indonesian seas is a better appreciation of the role of elevated tidal mixing in both transforming the incoming Pacific water masses and in modifying regional SST and global climate. In the Indonesian seas, large tidal currents interact with the rough topography and create strong internal waves at the tidal frequency, called internal tides that eventually propagate and dissipate. Somewhat uniquely, the Indonesian archipelago is the only region in the global ocean with strong internal tide generation in a semi-enclosed area. As a result, all of the internal (or baroclinic) tidal energy remains trapped locally inside the archipelago and is available for dissipation. Thus, the archipelago is one of the world's largest internal tide generation sites (10% of the global value) (Nagai and Hibiya, 2015).

As a result of internal tidal mixing, water masses are transformed when entering the archipelago (Ffield and Gordon, 1996; Hautala et al., 2001; Koch-Larrouy et al., 2007). Ffield and Gordon (1992) estimated from observations that vertical diffusivities of 10^{-4} m^2/s are needed to explain the transformation. Over this past decade, there has been a concerted internationally collaborative effort to better understand where, at what depths and under what conditions strong vertical diffusivities might occur in the Indonesian seas. It has been shown that it is critical for models to parameterize or include this mixing in order to get the air-sea coupling important to climate and regional ocean productivity correct (e.g., Jochum and Potemra, 2008; Koch-Larrouy et al., 2010). Yet large uncertainties remain in our current understanding of processes associated with internal tide generation and dissipation.

Tidal Mixing Signatures From SST

Two decades ago Ffield and Gordon (1996) provided some of the first direct evidence of strong tidal mixing in the Indonesian seas. During the fortnightly spring-neap cycle, stronger tidal currents occur during spring tides that enhance mixing such that the colder subsurface water lowers the observed SST. Ffield and Gordon (1996), using limited field observations, suggested that much of the stronger tidal mixing occurs in the internal Banda Sea. Yet, subsequent limited microstructure measurements in the central Banda Sea (Alford et al., 1999) found no fortnightly signal in kinetic energy dissipation, and low diapycnal diffusivity. Ray and Susanto (2016) recently revisited the Ffield and Gordon (1996) premise, albeit using higher-spatial and temporal resolution remotely sensed SST data and concluded that the strongest fortnightly SST patterns are mostly localized to narrow straits, channels and sills, especially along the exit passages of the ITF (**Figure 9**) where strong internal waves have been observed (Susanto et al., 2005; Aiki et al., 2011; Matthews et al., 2011) and along the southern boundary of the Sulu Sea (Tessler et al., 2012). Numerical models predict that tidal currents are large in the same regions and tidally induced mixing is anticipated (**Figure 9**; Koch-Larrouy et al., 2007; Nagai and Hibiya, 2015).

Mixing Estimates From Direct Measurements

The Indonesian Mixing program (INDOMIX 2010) was designed to directly quantify the very strong mixing that transforms Pacific waters into the isohaline Indonesian waters in the Indonesian archipelago (Koch-Larrouy et al., 2015). Turbulent dissipation rates and associated mixing were estimated and analyzed combining physical and geochemical in-situ observations: (1) direct measurements of the dissipation using a Velocity Measuring Profiler (VMP) microstructure system, (2) use of density-based fine-scale methods applied to CTD and XCTD data, and (3) study of the vertical distribution of natural radionuclides (radium isotopes and actinium-227). Data were collected at contrasting stations within the Indonesian archipelago: above energetic straits or in relatively quiescent large basins. Both the fine-scale and micro-scale methods identified very strong energy dissipation levels above the straits, ranging between [10^{-7}, 10^{-4}] W kg^{-1}. Enhanced mixing is found to occur preferentially above rough topography and lower mixing occurs further away from the generation sites, for example at the center of the Halmahera Sea ([10^{-9}, 10^{-8}] W kg^{-1}) and within the Banda Sea ([10^{-11}, 10^{-10}] W kg^{-1}). Vertical eddy diffusivities ranged between 5.10^{-4} and 5.10^{-1} m^2 s^{-1}, except

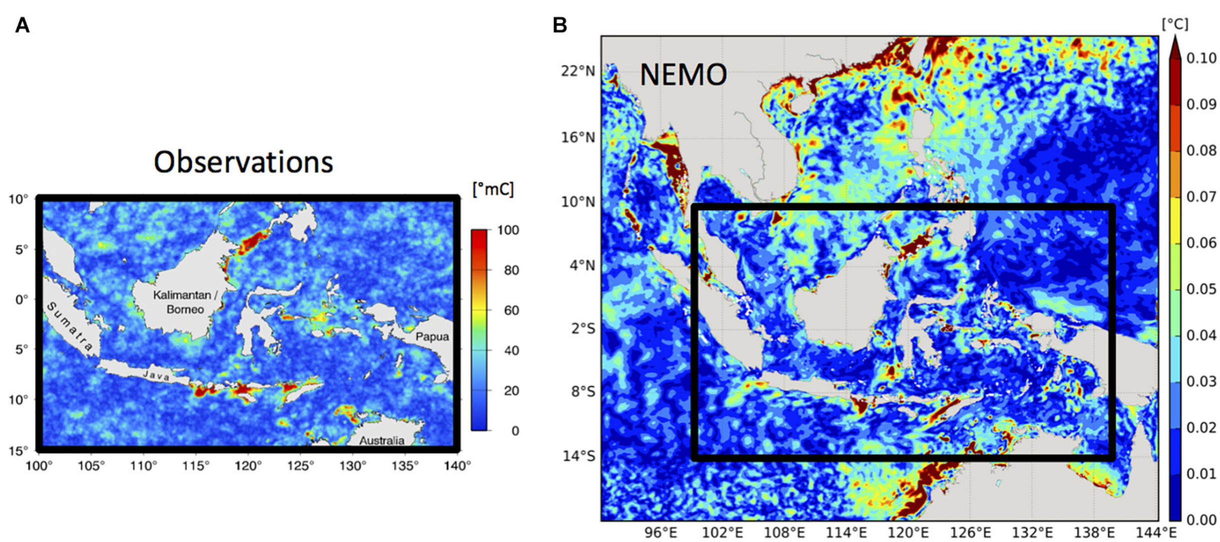

FIGURE 9 | Amplitude of the spring-neap (MSf) tidal component in sea surface temperature, extracted from **(A)** over 12 years of MUR-SST data (in °mC) (Figure from Ray and Susanto, 2016) and from **(B)** the NEMO INDESO model (in °C). High amplitude (red) indicates strong tidal mixing. (Figure from Nugroho et al., 2017. Permission obtained from Elsevier).

in the Banda Sea where values are similar to that of the open ocean (10^{-6} m^2 s^{-1}). Surface mixing at the base of the mixed layer is very strong with values between [10^{-4}, 10^{-3} m^2 s^{-1}]. In general, while the three methods broadly agreed, the fine-structure method differed in the depth of mixing from the other methods and also detected a larger range in the dissipation between stations.

The Challenges of Modeling Tidal Mixing in the Indonesian Seas

Climate models need to account for the intensified ocean mixing to properly represent the mean state and variability of the tropical climate system (Koch-Larrouy et al., 2007, 2010; Sprintall et al., 2014). However, in order for models to account for this mixing several challenges need to be overcome. Internal tide scales cover from kilometers for their propagation to centimeters/millimeters for their dissipation. A model capable of simultaneously resolving these scales does not yet exist.

Koch-Larrouy et al. (2007) implemented a tidal mixing parameterization in the NEMO OGCM specifically for the Indonesian archipelago that produced the heterogeneous vertical diffusivities in good agreement with the INDOMIX observations (Koch-Larrouy et al., 2015). However, parameterization represents only a first step toward accounting for the mixing induced by the internal tides. In reality, the dissipation may not occur exclusively locally but rather some fraction could dissipate in the far field. Also, dissipation may vary in time following the cycling of the surface tides. Such limitations and the increase of model resolution encouraged scientists to force their models using explicit tidal forcing in the Indonesian seas (e.g., Robertson and Ffield, 2005; Kartadikaria et al., 2011; Castruccio et al., 2013; Nagai and Hibiya, 2015; Nugroho et al., 2017) with model resolutions between 5 and 10 km.

Models that do not account for the additional mixing induced by the tides produce large biases in the water masses in the Indonesian region (Schiller et al., 1998; Schiller, 2004; Koch-Larrouy et al., 2007, 2008; Sasaki et al., 2018). The addition of explicit tidal forcing produces an intensified mixing that better reproduces the isohaline Indonesian water in the Banda Sea (**Figure 10**; see also Kartadikaria et al., 2011; Castruccio et al., 2013; Nugroho et al., 2017). However, quite surprisingly the model that includes the explicit tidal forcing (Nugroho et al., 2017) produces almost the same mixing as in the coarser resolution model that parameterizes the internal tides (Koch-Larrouy et al., 2007; **Figure 10**). This suggests that the processes involved in the dissipation of the internal tides are not being fully resolved. The question then is how is the model able to create mixing when no specific internal tides are active in the model? Is the spatial distribution of the tidal mixing in the model correct? Is mixing occurring at the correct rate over the evolutionary time span of the internal tides? To tackle this issue, we briefly discuss the advances and limitations of various models, that handle tidal mixing in various ways and are of various horizontal resolutions, over the life cycle of the internal tides in the Indonesian seas.

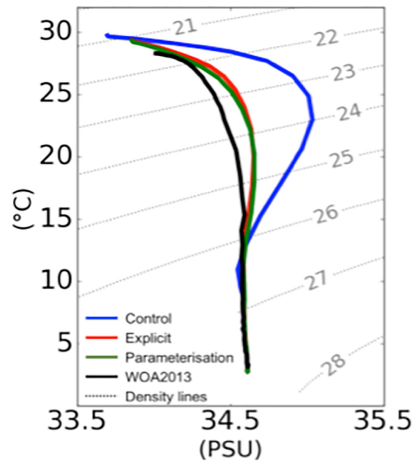

FIGURE 10 | Temperature-salinity diagram of averaged properties in the Banda Sea (124.75°E–130.83°E; 6.65°S–4.41°S) from the NEMO simulation that does not include tides (CTRL: blue line); the NEMO simulation that includes explicit tides (EXPL: red line); the NEMO simulation that parameterizes tides (PARAM; green line) and the WOA 2013 observed climatology (Figure from Nugroho et al., 2017. Permission obtained from Elsevier).

Generation

Model-based estimates give ranges of 85–110 GW of energy transfer to the internal tide within the Indonesian seas, about 10% of the total global generation (Nagai and Hibiya, 2015). Niwa and Hibiya (2011) show that using a 9 km (∼1/12°) resolution, their model is able to generate only 75% of the internal tides. With a 4 km (∼1/36°) resolution, the model generates 90% of the internal tides and explicitly solves the internal tides with some accuracy. Compared to the FES2014 global tidal model at 1/12° resolution with 11 tidal components, NEMO reproduces 75% of the total estimated energy (Nugroho et al., 2017), whereas at 1/100° resolution the MITgcm with only M2 reproduces ∼95% of the M2 estimate (Nagai and Hibiya, 2015). For these three models, generation sites are the strongest at the entrance eastern passages of Halmahera, Lifamatola, Sula and Buru straits, the Sangihe Island chain, the Sulu Strait and Dewakang sill in Makassar Strait (**Figure 11**). Strong internal tides are also produced within the exit passages of Ombai, Lombok, and Sumba Straits.

The baroclinic component of the tides extracted from the sea surface height of the NEMO (Nugroho et al., 2017) and HYCOM (Ansong et al., 2015), both at 1/12° resolution, and the MITgcm (Nagai and Hibiya, 2015) at 1/100° resolution compares well to altimetry data (**Figure 12**). Regional differences exist between the models, such as above Dewakang sill in Makassar Strait and in the Flores Sea, and the amplitude of the baroclinic tides in NEMO is weaker than HYCOM. Although HYCOM is more realistic, the amplitude of the tidal signature is still too strong compared to the observations. The MITgcm also gives too large sea surface height elevations (Nagai and Hibiya, 2015). Differences are likely due to the parameter choices between models, although it is not yet fully understood why these differences occur.

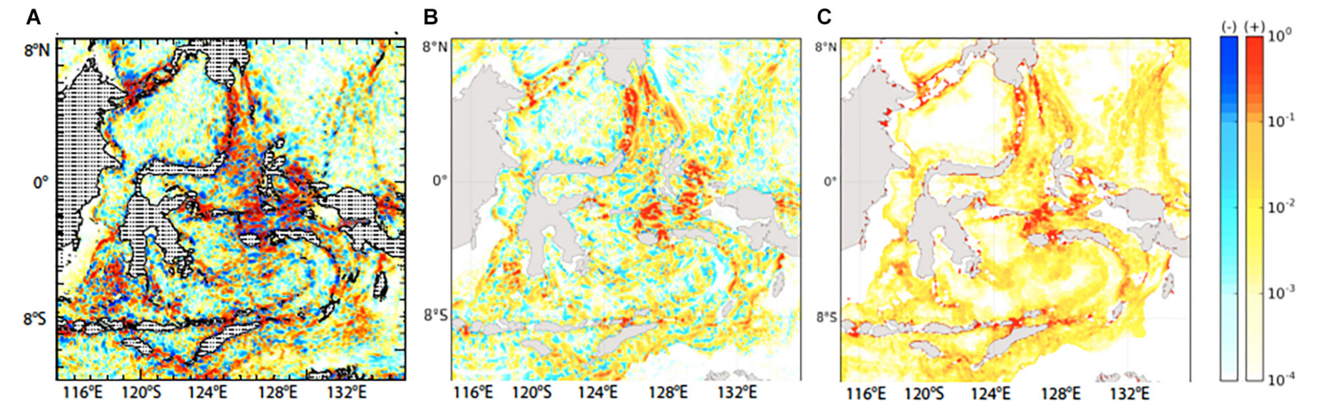

FIGURE 11 | Generation regions of internal tides, which correspond to the energy transfer from barotropic to baroclinic tides (Logarithmic scale, Wm^{-2}), from **(A)** MITgcm (1/100°), (Figure from Nagai and Hibiya, 2015), **(B)** INDESO NEMO and **(C)** FES2014 (Figure from Nugroho, 2017. Permission obtained from author). Red colors are likely generation areas whereas blue might be an artifact of the model and/or the numerical calculation due to possible non-linear interaction between the surface and internal tides.

Propagation

Once generated, part of these internal tides may propagate. But the fraction of the waves that dissipates locally or propagates further away to dissipate in the far field remains a big unknown within the Indonesian seas. The velocity for the four tidal components (M2, K1, S2, O1) in the NEMO 1/12° (9 km) model with explicit tidal forcing shows the clear propagation of mode 1 and 2 internal tides from the Sangihe Islands and Lifamatola Strait (Nugroho et al., 2017; **Figure 13**). Note that at this resolution, the model is only capable of resolving the mode 1 and mode 2 internal tides with length scales of ∼100 and ∼50 km, respectively (Nugroho, 2017). NEMO seems to produce larger baroclinic fluxes than the MITgcm (**Figure 14**). In Sulawesi, internal tides coming both from the Sangihe Ridge and Buru Straits interact and almost fill the entire sea, in quite good agreement with altimetry and SAR images (Nugroho et al., 2017). Strong propagation is also found from the Sula, Buru and Ombai Straits filling the western Banda Sea, while northern propagation from Lifamatola and Sumba Straits may act to transform Pacific water masses (Koch-Larrouy et al., 2007). Still, this comparison with altimetry is only qualitative, and more dedicated field studies are needed to validate the path and energy of the propagating tides.

Dissipation

Models can provide 3-dimensional maps of dissipation, to evaluate how much mixing is produced in the local vs. far field (**Figure 14**, color shading). However, many models do not have the resolution nor physically based parameterization to constrain this field. Both the NEMO 1/12° (Nugroho et al., 2017) and the MITgcm 1/100° (Nagai and Hibiya, 2015) find dissipation is stronger above generation sites and in the near field than further away. In NEMO most of the tidal energy is dissipated in the interior by horizontal momentum dissipation (Nugroho et al., 2017) while in reality one would expect dissipation through vertical processes. Only about 20% of the mixing remains for far field dissipation, and this seems to mainly occur in the Banda Sea. Nagai and Hibiya (2015) found about 50–75% of the dissipation occurs locally near the straits and sills where the tides are generated, although they do not distinguish between vertical and horizontal dissipation processes. In both studies, there is a residual of an unphysical source of dissipation that may come from numerical dissipation [20% in the MITgcm model of Nagai and Hibiya (2015) and 40% in the NEMO model of Nugroho et al. (2017)].

The NEMO model and the INDOMIX data are surprisingly in good agreement in terms of tidal energy dissipation estimates within the straits (Nugroho et al., 2017). However, in regions further away from the generation sites where INDOMIX found no evidence of intensified mixing, the model produces too strong mixing. The bias comes from the lack of specific set up of internal tides in the model and a too strong baroclinic flux (e.g., **Figure 14**). Improving the modeled dissipation and validating the model energy fluxes is a theme of ongoing active research.

Tidal Mixing Feedbacks to Climate and Biology

The mixing induced by the simulated tides produces a significant SST cooling of 0.3–0.8°C in the areas of internal tide generation. Additional cooling occurs in models that include explicit tidal forcing due to the exchange of water mass properties (e.g., Malacca Strait) and bottom dissipation (e.g., over the Northwest Australian shelf). The simulated and observed cooling is stronger in austral winter when the thermocline is shallower (Kida and Wijffels, 2012; Nugroho et al., 2017). This cooling increases ocean heat uptake by ∼20 W m^{-2} and reduces the locally driven deep atmospheric convection and the associated rain activity by as much as 20% (Jochum and Potemra, 2008; Koch-Larrouy et al., 2010; Sprintall et al., 2014). Tidal mixing within the Indonesian archipelago has also been shown to influence the discharge and recharge of upper-ocean heat content in the Indo-Pacific region (Koch-Larrouy et al., 2010). This in turn regulates the amplitude and variability of ENSO, the IOD and the MJO. Indeed, models

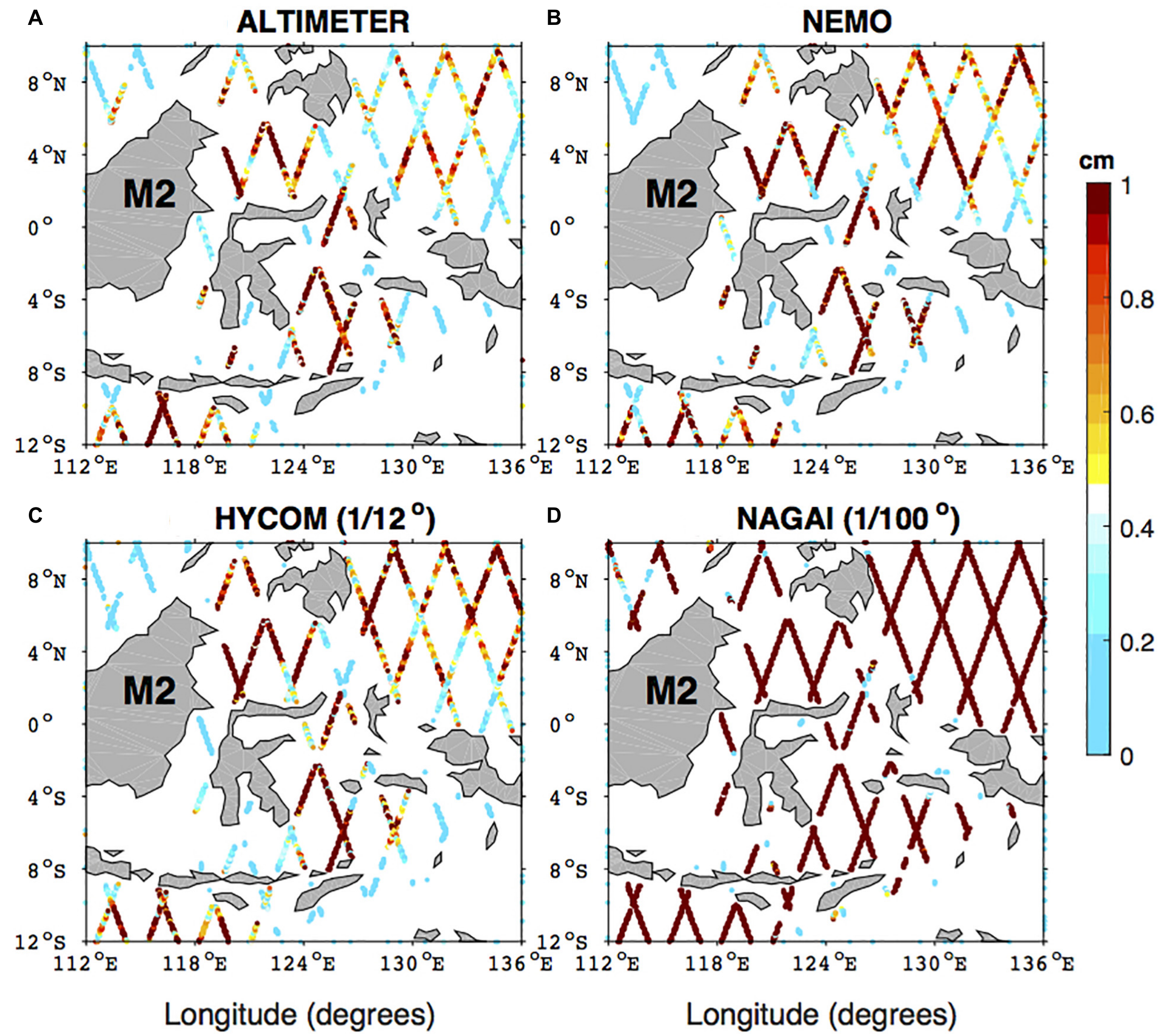

FIGURE 12 | Semi-major axis of the velocity (cm s^{-1}) for the **(A)** M2, **(B)** K1, **(C)** S2 and **(D)** O1 tidal constituents in the NEMO 1/12° INDESO model configuration (Figure from Nugroho, 2017. Permission obtained from author).

that include tidal mixing have improved representation of ENSO, IOD and MJO patterns (Koch-Larrouy et al., 2010; Sprintall et al., 2014). However, in reality, the complexity of the atmospheric response to enhanced mixing remains poorly understood and is a topic of ongoing research.

The impact of mixing on biological activity has also not yet been fully studied, but it could be speculated that the vertical mixing would have a significant impact on phytoplankton blooms through the upwelling to the surface of nutrient-rich water. INDOMIX found that vertical mixing (directly measured by the VMP) is the dominant process transforming the nutrients (nitrate, silicate, phosphate) and the vertical distribution of oxygen measured in the Halmahera Sea. Very strong mixing is needed in this small sea where the residence time is quite rapid (2 days). As such, vertical mixing dominates over the biogeochemical processes in explaining the transformation of the vertical distribution of nutrients and oxygen from the Pacific to the Halmahera Sea. More concurrent physical and biogeochemical in-situ data are needed to corroborate this and determine whether this occurs in other regions of the maritime continent.

PATHWAYS TOWARD AN ITF INTEGRATED OBSERVING ARRAY

Long term monitoring of the ITF and the Indonesian seas remains both a logistical and technological challenge. The ITF differs on time scales of interest from diurnal to decadal with phase differences from strait to strait. Clearly a multi-platform approach would offer the best strategy for developing an integrated array to measure the mass, heat and freshwater fluxes of the ITF. Here we break up the challenge of developing

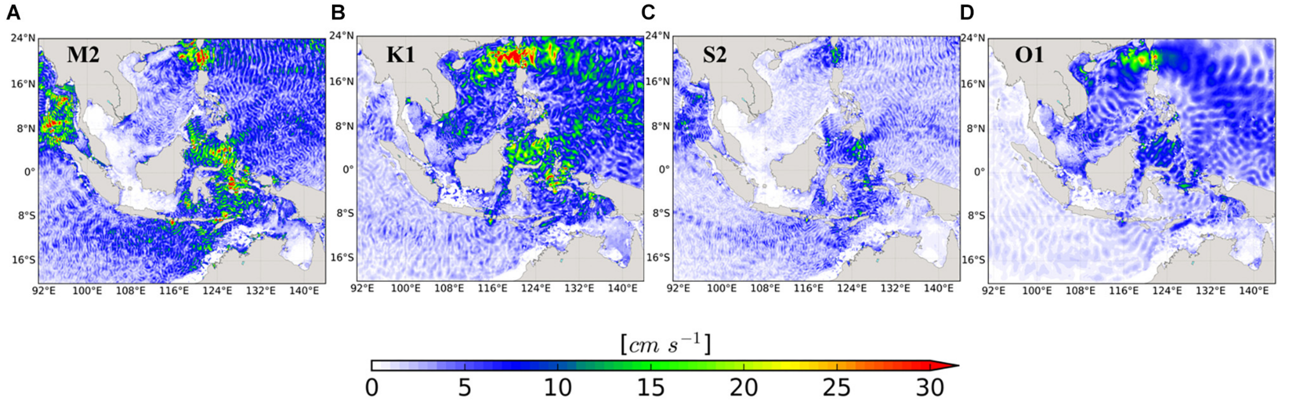

FIGURE 13 | The baroclinic tides (cm) from **(A)** along-track TOPEX/Poseidon and Jason satellite altimeter data (1992–2009) **(B)** the NEMO 1/12° INDESO model configuration (Nugroho et al., 2017) and **(C)** the HYCOM 1/12° model configuration (Ansong et al., 2015) and **(D)** the MITgcm (1/100°, Nagai and Hibiya, 2015). Details of the approach used to extract baroclinic tides from the HYCOM output and along-track altimeter data are provided in Shriver et al. (2012). Model output are interpolated to the altimeter tracks. For models and altimeter output, spatial band-pass filtering along the altimeter tracks is used to extract the M2 internal tide signals with wavelengths in the 50–400 km range. Only locations with sea floor depth greater than 1500 m are plotted. (Figure from Ansong et al., 2015).

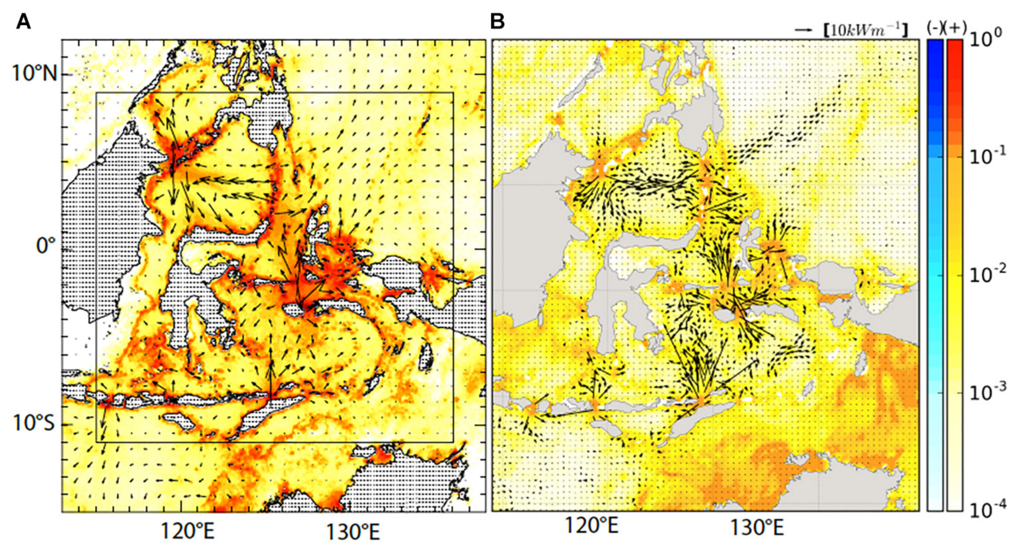

FIGURE 14 | Model predicted distribution of the depth-integrated baroclinic energy flux (kW/m; vector) and baroclinic energy dissipation (W/m^2 shading) from **(A)** NEMO (1/12°) (Figure from Nugroho, 2017. Permission obtained from author) and **(B)** the MITgcm (1/100°) (Figure from Nagai and Hibiya, 2015).

an observing array into several targets and possible approaches that use both existing platforms and emerging new technologies.

ITF Volume and Climate Fluxes

Prior to INSTANT, the main throughflow passages were monitored over different years and for varied lengths of time, making it impossible to assemble a simultaneous picture of the multiple corridors of the ITF that captured the inherent variability. INSTANT revealed the need for concurrent measurements in the major inflow and outflow passages in order to depict the evolving partitioning of transport through the major passages, and thus the full ITF. However, such an array is logistically difficult (e.g., ship-time requirements) and expensive to maintain. In addition there are a number of challenges faced by the various platforms that are used by a monitoring array for resolving the aspects of the ITF flow.

Moorings excel at providing a continuous time series of the velocity to the depths of the interocean exchange (∼1250 m) in the narrow and tidally dynamic passageways of the ITF. Technological advances in moored instrumentation and floatation offers some optimism that a simplified sparse moored array could capture the key transport variability. Coverage of each of the major passages (Makassar, Lifamatola, Halmahera, Lombok, Ombai and Timor) is desirable. Measurements of the eastern inflow via the Halmahera Passage is particularly sparse, and more exploratory work is needed to better target longer term monitoring sites. Simplified velocity moorings comprising of 2–3 long-ranging ADCPs with low-tilt floatation (to keep the ADCPs vertical) can be used to monitor the flow. The lack of a surface toroid to prevent detection has made it difficult for real-time transmission of the subsurface data for model forecasting and assimilation purposes. However, acoustic modems could be used to return the data before a full mooring turn-around and potentially reducing the amount of ship-time required.

Transport integral calculations from 1 to 2 moorings in each passage requires assumptions about the extrapolation of the single-point measurements across the passage to the side-wall boundaries and interpolation between point-wise instruments along the mooring line with depth. Thus, to convert a moored velocity record into net mass transport through the strait, the moored measurements need to be augmented with more detailed observations of cross-strait structure. Better knowledge of the width and stability of the side-wall boundary friction layer, the typically unmeasured bottom layers and improved characterization of the cross-strait structure in each passage through shipboard velocity surveys will greatly reduce uncertainty in transport estimates and help modelers make better parameter choices in simulations.

The missing near surface measurements might be achieved through acoustic tomography or high frequency radar arrays. The main advantage of these technologies is that they are truly integrative (no across strait interpolation/extrapolation is needed), they have the required high frequency sampling and they could deliver data in real time. Further piloting of coastal tomographic and high frequency radar arrays in the straits overlapping with the moored array is recommended. Finally, submarine cables that exist within the Indonesian seas also offer a potential platform to monitor ocean transport, as has been used for many decades in the Gulf Stream as part of the RAPID array (see AMOC CWP).

The interocean flux of heat and freshwater induced by the ITF does not depend just on the net transport, but also on the shape of the velocity, temperature and salinity profiles. While some proxies have been developed for ITF net volume fluxes (Sprintall and Revelard, 2014; Susanto and Song, 2015; Li et al., 2018), large changes in the profile of the ITF means that volume transports and heat/freshwater transports are not always well correlated, particularly at seasonal and longer timescales. Because of fishing pressures and vandalism, most moorings do not have a surface expression and so they do not capture the temperature and salinity of the upper 100 m or so. This means that moored arrays alone are unable to fully resolve the important heat and freshwater fluxes associated with the ITF. Heat transports can, however, be effectively estimated if the transport per unit depth profile is well constrained and combined with climatological temperature observations, such as from XBT transects or Argo profiles. Thus observations of the transport profile in the key ITF straits is essential to constrain the ITF heat fluxes. Less is understood about ITF freshwater flux variability. Yet variations in heat and freshwater fluxes bear directly on ocean-atmosphere exchange in the Indian Ocean (e.g., Vranes et al., 2002) so monitoring these changes may provide insight into tropical climate processes.

Ocean gliders also present new opportunities for synoptic surveys of velocity and properties in the Indonesian Seas to complement hydrographic and moored measurements. Autonomous operation and satellite communications mean that a glider could be launched and operated from a shore command post to steadily build a long-term time series of temperature, salinity, depth-integrated velocity and a suite of biogeochemical EOVs in the upper 1000 m across a strait or within the seas. Nonetheless, the relatively slow sampling of the glider means that high frequency variability such as internal waves are aliased into the lower frequency signals. The strong flows across straits also present a challenge for glider navigation although some strategies have been developed to successfully observe in other boundary current observing systems (e.g., Davis et al., 2012).

Downstream, the IX1 frequently repeated XBT line provides a valuable long-term record that captures the monthly upper ITF geostrophic response to the major climate modes (Liu et al., 2015), but its shallow sampling (700 m) and lack of salinity limits the accuracy of these geostrophic and heat transport estimates. In addition, large internal tides within the enclosed basins of the Indonesian seas are challenging for accurate geostrophic calculations. Careful processing is required to remove this signal from the XBT time series (e.g., Wijffels et al., 2008). While increased salinity observations from Argo may help, enhanced resolution of salinity observations near the boundaries is also needed. Thus exploring use of a CTD on a moving vessel profiler (MVP) and perhaps installation of an underway ADCP on IX1 is recommended.

Hydrography of the Indonesian Seas

There remains a scarcity of temperature, salinity and biogeochemical profiles from within the Indonesian seas. This precludes building even a seasonal picture of water mass variability, let alone tracking changes from year to year. Profiling floats (e.g., Argo) sampling of the Indonesian seas remains a challenge due to the complex topography, narrow straits, and the high likelihood of float capture or damage due to fishing operations. However, a positive development over the past decade is that the time a float spends at the sea surface to transfer data to satellite has dramatically decreased with the transition to high-bandwidth Iridium communications that significantly improves the chance of float survival (See Argo CWP). With its enclosed bathymetry, floats parked below the major sill depths (∼1200 m) are unlikely to leave the internal Indonesian seas. A stable deep water mass is also advantageous in that it allows sensor drift to be easily diagnosed and corrected.

Profiling floats also offer the opportunity to include additional sensors (e.g., microstructure, velocity biogeochemistry, rainfall and wind) beside the standard temperature-salinity (T-S). For example, parameterization of mixing from shear and strain profiles is widely used (e.g., Whalen et al., 2012) to infer dissipation of turbulent kinetic energy from the fine-scale (order 10 m and larger) variability in velocity and density profiles (Polzin et al., 1995). Passive Aquatic Listener (PAL) technology on profiling floats, gliders and other platforms provide estimates of wind speed and rainfall (Riser et al., 2008; Yang et al., 2015) and offer a tremendous opportunity to obtain valuable air-sea flux components within the internal Indonesian seas. Biogeochemical-Argo (BGC-Argo) sensors measuring dissolved oxygen, nitrate, pH, Chlorophyll a, suspended particles and downwelling irradiance in the Indonesian Seas would also provide new and critical information on marine living resources to guide management of fisheries resources.

A float array of 6 profilers operating in the internal seas (1 in each of the Moluku, Flores, Sulawesi Seas and 3 in the Banda Sea) would be a useful initial backbone array. Several or all of these might carry biogeochemical sensors (BGC Argo CWP), which would greatly accelerate our understanding of regional productivity, carbon uptake, acidification rates and help interpret satellite ocean color data. Occasional ship-based high precision surveys of full depth biogeophysical parameters would be useful to help validate the data from the float array.

Mixing and Fine-Scale Observations

How, where and when water masses are modified and mixed in the Indonesian seas is still not known in detail, as the mixing measurements remain sparse. Of key importance to climate on many timescales is the drawdown of SST via enhanced heat transport through the thermocline driven by tidal mixing that have a major impact on both water-masses and surface heat fluxes. While a qualitative insight can be gained from fine-scale structures in density profiles delivered by profiling floats or gliders, a quantitative understanding of the processes at work requires fine-scale *velocity* observations and even more desirable, dissipation measurements. Direct measurements of dissipation will drive forward our understanding of local mixing and will guide parameterizations and challenge models that simulate these processes. However, direct estimates of vertical mixing through microstructure observations are costly and limited to research vessel operations (e.g., Waterhouse et al., 2014; Koch-Larrouy et al., 2015) and moorings (e.g., Moulin et al., 2018).

To measure the mixing processes near the generation sites, a combination of moorings and ship-based dissipation measurements are needed. Some insight into the generation processes can be gained from fine vertical scale (15 m) and high frequency measurements of the internal tides in the straits (velocity, density (T/S) at 10 minutes or higher). These measurements could coincide with the transport moorings described above that are located near some of the major generation sites. Gliders equipped with CTD, velocity and dissipation sensors could also collect detailed information across the generation sites, but the very strong tidal currents (1–2 knots) which drive the generation will prove a huge challenge to pilot the gliders. Ship-based surveys using microstructure, CTD and shear profilers are also needed, where stations are sampled over a tidal cycle.

EM-APEX (ElectroMagnetic Autonomous Profiling EXplorer) are enhanced Argo floats that include an electromagnetic subsystem to measure horizontal velocity relative to a depth-independent offset, in addition to temperature and salinity. Combining the relative velocity profiles with GPS position information delivers absolute horizontal velocity, with vertical spacing of samples of around 3 m (Phillips and Bindoff, 2014). These shear measurements can be used to characterize the internal wave field and estimate vertical mixing (Meyer et al., 2015, 2016). A fleet of EM-APEX floats profiling synchronously will yield a snapshot of the velocity, density and mixing structure of the interior seas, offering the potential to capture ray paths of internal tidal beams in adjacent float profiles. Due to power limitations, at present these are not suitable for long-term monitoring, but a tremendous amount could be discovered about the extent of radiated energy and its dissipation over a fixed 3-year campaign. This would be long enough to capture the interactions of the seasons, the intraseasonal and spring-neap tidal variations. Direct dissipation measurements are also being piloted on profiling floats (Argo CWP), and as this technology is matured, floats in the internal seas should be equipped with these sensors.

Sea Level, SSS and SST

Satellite missions now deliver sea level anomalies, SST and SSS routinely and globally. However, these space-based observations require *in situ* validation, and the signal is often degraded by the presence of cloud, aerosols and precipitation, that are common in the Indonesian seas. High temporal resolution surface flux measurements including winds, precipitation and heat flux components critical for model experiments and budget closures are lacking. Long records and high-quality reference measurements can be of great value in validating satellite retrievals and help in assessing climate records produced from a series of space-based sensors.

While the region has good coverage of high-quality sea level sites (Sealevel CWP), *in situ* SST and SSS data from the Indonesian seas are rarely available. Surface drifter life is short in the internal seas, and Argo floats at present sample too infrequently and are too sparse to help de-bias the satellite data. In addition, because of the fishing and vandalism pressures as well as the strong dynamic conditions, there are few moored air-sea flux reference stations in the internal Indonesian seas that might also be useful for satellite validation (e.g., see TPOS CWP). Underway thermosalinographs (TSGs) and meteorological packages from ships of opportunity could be very helpful in filling this gap and potentially could be operated on the extensive ferry system that operates throughout the Indonesian seas. Sustained SST/SSS and meteorological observations from offshore sites, such as the RAMA array (see INDOOS CWP), the wave rider or Tsunami warning sites, would also provide a valuable record.

FINAL THOUGHTS AND RECOMMENDATIONS

Understanding the variation in the ITF is crucial for understanding the coupled air–sea climate system, and the storage of the heat and fresh water that is ultimately redistributed throughout the world oceans by the thermohaline circulation. Yet despite its importance to regional and global climate, observations from this region remain limited. In this final section we suggest a way forward in the development and implementation in the coming decade of a sustained monitoring array for the transport of mass and properties along the various streams of the ITF as well as to increase our understanding of the various processes like upwelling and tidal mixing that play an important role in the water mass transformation of the region. So, while the convoluted bathymetry of the Indonesian seas means that moorings will likely continue to be the workhorse of any backbone transport array for the near future, our sustained array will propose a multi-platform approach including additional surveys, process studies and new technology that will go some ways to fill in the gaps that cannot be accomplished through moored arrays alone.

Recommended Next Steps

Here we provide a detailed plan that provides a framework for the needed scales and parameters of a recommended observational strategy (**Figure 15**). We recognize that prior to implementation, some additional "process" study measurements might be valuable to consolidate our recommended monitoring array. For example, some short-term (1–2 years) mooring measurements in the eastern arcway along the Seram Sea that feeds into the Banda Sea as well as in the shallower export passages of Sape and Sunda Strait might enable a better assessment of the contributions of these pathways to the ITF. Similarly, some model simulations have suggested that internal tides generated in other regions of the Indonesian seas might contribute to strong mixing (e.g., round the islands surrounding the Seram Sea etc.) and so might also be targeted for microstructure measurements. In addition, a process study to discriminate the coherent and non-coherent baroclinic tides might be useful to determine the interaction between the baroclinic propagative tides with the background circulation and eddy field. So while these process studies might eventually better inform our general monitoring array, our initial strategy is to recommend the observational monitoring sampling that has our highest priority (**Figure 15**).

General Monitoring Array

Phase 1: Intensive pilot and tidal mixing study (3-years)

(1) Instrument the major inflow and outflow straits with full moored ADCP velocity coverage (and vertically dense T and S measurements) to capture transport for a period of around 3 years. The inflow passages should include both eastern and western pathways.
(2) Use the deployment/retrieval voyages to acquire across strait velocity measurements and dissipation observations.
(3) Pilot acoustic tomography and/or high frequency radar across a few shallow straits while the moorings are in place.
(4) Densely seed the internal seas with a mixture of EM-APEX dissipation measuring, BGC Argo and regular Argo floats (total of ∼8–10 floats).
(5) Encourage further mixing/dissipation, BGC and meteorological parameters from ship-based surveys during the campaign and from SOOP.

Phase 2: Replace with backbone

(1) Replace Phase 1 moorings with simpler velocity-only ADCP moorings designed for a 2-years maintenance schedule. Adjust mooring locations based on learnings from Phase 1. Explore potential of using shipboard communication or pop-up data pods to transmit collected data.
(2) Maintain a ∼6 profiling float array in the internal seas, possibly all with dissipation and BGC sensors.
(3) If float returns are reliable, assess and possibly discontinue the PX2 and IX22 frequently repeated XBT lines of the internal seas. Maintain the frequently repeated IX1 line in the Indo-Australian basin as a key multidecadal record and downstream check point and enhance with ADCP and salinity measurements.
(4) If successful, continue to develop coastal acoustic tomography and high frequency radar capability, with the potential to progressively take over transport monitoring in the shallower and narrower straits.
(5) Expand *in situ* SSS, SST and meteorological observations of the Indonesian seas, either using TSG and meteorological packages from SOOP or shallow moorings where possible.

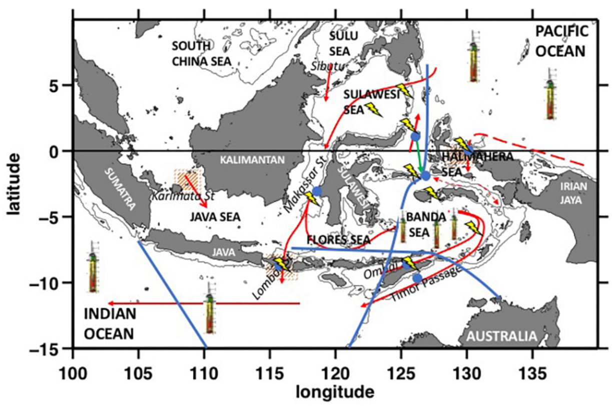

FIGURE 15 | Schematic of proposed intensive pilot study and enhanced mixing array for the Indonesian seas. The array includes (multiple) moorings in straits (blue dots); XBT transects (blue lines); acoustic tomography and/or high frequency radar (orange hatched); Argo/BGC/EM-APEX floats (float icon) and microstructure measurements (yellow lightening). Upper ocean current pathway is in red, lower pathway in green. Dashed lines indicate uncertain pathways.

Strategy for Enhanced Mixing Measurements

(1) Platforms: include shipboard microstructure profilers; fast response sampling by chi-pods on moorings; CTD/LADCP or yoyo stations (for strain); profiling floats with microstructure or fast-response sensors (e.g., EM-APEX).
(2) Sampling strategy: station sampling of at least 24 h for dissipation to capture diurnal modulation; tidally-resolving towed sections; temporal preference to sample during spring tides when signal strongest; longer time series to extract tidal components (>1 month to enable separation of M2 from S2).
(3) Locations: measurements at generation sites and along the path of the propagating tides:
    (a) Generation sites:
        (i) Eastern passages (Halmahera, Lifamatola, Sula and Buru straits).
        (ii) Western passages (Sangihe Ridge; Sibutut Passage; Makassar and the Dewakang Strait).
        (iii) Exit passages: Ombai, Lombok, and Sumba Straits.

(b) Further away from the generation sites along the propagation pathway:
   (i) Sulawesi Sea.
   (ii) Banda Sea (north of Ombai, south of Sula and Buru Strait).
   (iii) North of Lifamatola Passage.

(4) Companion Measurements
   (a) Density (targeting the thermocline) and horizontal velocity measurements at high frequency throughout the water column to quantify the baroclinic energy at generation sites and in the far-field.
   (b) Biogeochemistry information (e.g., nutrients, chlorophyll) to measure the effect of tidal mixing on potential enrichment and blooms in the surface layer.

Paths to Governance and Implementation

The recommended plan Phase 1 could benefit by being partially implemented in association with YMC or under the international IIOE-2 program. Our recommendations address many IIOE-2 priority research areas identified in *Theme 4: Circulation climate variability and change* (Hood et al., 2015).

Real success will rely on a closely integrated modeling and observational plan. Development of a novel set of model and analysis tools will enable examination of transport pathways, mixing processes, and make it possible to test hypotheses of remote dynamical teleconnections that are difficult to address from observations alone.

Finally, it is important to recognize that one nation alone could not expect to successfully execute and accomplish the recommended sustained monitoring strategy. The need for international co-operation to skillfully implement and fulfill the wide-ranging plan is evident. Indonesia will be a principal partner aiding in the co-ordination and facilitation of regional and political mechanisms to sustain the monitoring array, as well as to help freely deliver and distribute the data set for operational use and scientific analysis. While the logistical and organizational collaborations of the sustained array will also be achieved at senior levels of the Indonesian government, the involvement of both Indonesian and international students and early career scientists will be critical to the success in sustaining and evolving the array. While insights and quantification of transport controls and mixing processes in this key region will have application in global modeling systems used for ocean and climate forecasts, it is also expected that a significant part of the outcome of this sustained array will be to improve local marine resource management and conservation practices in the maritime continent.

AUTHOR CONTRIBUTIONS

JS led the writing, editing, and organization of the manuscript. AG, SW, MF, and SH led and wrote sections. AK-L and HP led and wrote significant subsections. DN, AN, KP, RS, BS, DY, NR, SS, AK, ZA, AW, HZ, TN, JA, RB-B, JC, FL, BKA, AR, and AS contributed to the writing of sections. All authors contributed comments.

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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.2019.00257/full#supplementary-material

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REVIEW
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Constraining the Oceanic Uptake and Fluxes of Greenhouse Gases by Building an Ocean Network of Certified Stations: The Ocean Component of the Integrated Carbon Observation System, ICOS-Oceans

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The European Research Infrastructure Consortium "Integrated Carbon Observation System" (ICOS) aims at delivering high quality greenhouse gas (GHG) observations and derived data products (e.g., regional GHG-flux maps) for constraining the GHG balance on a European level, on a sustained long-term basis. The marine domain (ICOS-Oceans) currently consists of 11 Ship of Opportunity lines (SOOP – Ship of Opportunity Program) and 10 Fixed Ocean Stations (FOSs) spread across European waters, including the North Atlantic and Arctic Oceans and the Barents, North, Baltic, and Mediterranean Seas. The stations operate in a harmonized and standardized way based on community-proven protocols and methods for ocean GHG observations, improving operational conformity as well as quality control and assurance of the data. This enables the network to focus on long term research into the marine carbon cycle and the anthropogenic carbon sink, while preparing the network to include other GHG fluxes. ICOS data are processed on a near real-time basis and will be published on the ICOS Carbon Portal (CP), allowing monthly estimates of CO_2 air-sea exchange to be quantified for European waters. ICOS establishes transparent operational data management routines following the FAIR (Findable, Accessible, Interoperable, and Reusable) guiding principles allowing amongst others reproducibility, interoperability, and traceability. The ICOS-Oceans network is actively integrating with the atmospheric (e.g., improved atmospheric measurements onboard SOOP lines) and ecosystem (e.g., oceanic direct gas flux measurements) domains of ICOS, and utilizes techniques developed by the ICOS Central Facilities and the CP. There is a strong interaction with the international ocean carbon cycle community to enhance interoperability and harmonize data flow. The future vision of ICOS-Oceans includes ship-based ocean survey sections to obtain a three-dimensional understanding of marine carbon cycle processes and optimize the existing network design.

Keywords: ocean observation, network design, CO_2 fluxes, flux maps, carbon sink

INTRODUCTION

More than a century of research on GHGs has convincingly proven that anthropogenic activities lead to global warming (IPCC, 2014). In the past three decades, research on GHGs has also become part of the international political and societal agenda. As such, there is a strong commitment from the community to continue improving relevant research and at the same time identify possible mitigation and prevention activities. The European research infrastructure "Integrated Carbon Observation System" (ICOS) provides high quality observations of GHGs (in particular CO_2) from across Europe and its surrounding waters. ICOS further aims to stimulate relevant research and technological development, and interacts with the climate science communities as well as with policy bodies. ICOS intends to be the European hub for GHG research and to provide products for a better understanding of GHGs in the Earth system. The first concept toward the ICOS infrastructure was presented in 2006. **Figure 1** shows the timeline and important milestones of ICOS.

ICOS is a pan-European network and a ERIC legal entity with more than 100 measuring stations from 12 countries. The stations are distributed across Europe and adjacent oceans and seas, from the Arctic territories (Zeppelin & Hausgarten Observatories) to the Equatorial Atlantic (Cape Verde Ocean Observatory & SOOP France-Brazil), and in the Southern Ocean (SOOP Polarstern). The network provides the operational infrastructure necessary for high quality GHG observations and consequently facilitates innovative science and research. The network's design and operation are under constant review, with the aim of increasing the level of confidence in the data and reducing associated uncertainties. The network is split into three Thematic Centers (TCs) [atmosphere (ATC), terrestrial ecosystem (ETC), and ocean (OTC)], enabling specialists in each domain to develop the best methods and practices to achieve the goals of ICOS. Each TC has an associated Monitoring Station Assembly (MSA) which represents the interests of the measuring community. The TCs set specific, uniform, and stringent operational criteria based on current best practices, which are agreed upon with their respective MSAs. The formal decision body is the GA where the member states are represented. The general assembly (GA) meets twice a year and the TCs report to the GA. The development of the initial stages of ICOS, up until the beginning of the ICOS ERIC 1^{st} Period (2016) was fulfilled within the scheduled timeline. From the beginning of the operational period until the red line in **Figure 1**, 48 out of 134 stations (approximately 36%) from all domains have received the official ICOS label, meaning that they are delivering to the high ICOS standards. This index, however, is not entirely representative of the overall ICOS progress. Developments like the setup of the Central Analytical Laboratory (CAL), the setup of the Carbon Portal (CP), the labeling protocols, the uniformity of operations in all domains, and the very high quality of the produced data highlight how much ICOS has developed. Currently, ICOS is in the important first operational phase and the number of stations that have received the ICOS label (see section "Labeling") is growing constantly.

Each measurement station in the network is nominated by the relevant member state and is then "labeled" as being able to provide data of high quality, following a thorough review by the

Abbreviations: ASV, autonomous surface vehicle; ATC, Atmospheric Thematic Centre; CP, carbon portal, https://www.icos-cp.eu/; DIC, dissolved inorganic carbon; EMSO, European Multidisciplinary Seafloor and Water Column Observatory; ENVRI, Environmental Research Infrastructure; ERIC, European Research Infrastructure Consortium; ESFRI, European Strategy Forum on Research Infrastructures; ETC, Ecosystem Thematic Centre; FOSs, Fixed Ocean Stations; GA, general assembly; GHG, greenhouse gas; GLODAP, Global Ocean Data Analysis Project; GOOS, Global Ocean Observations System; GO-Ship, Global Ocean Ship Based Hydrographic Investigations Program; HO, Head Office; ICOS, Integrated Carbon Observation System; MFT, marine flux tower; MSA, Monitoring Station Assembly; NDIR, non-dispersive infrared; NOC, National Oceanography Centre; NRT, near real time; OTC, Ocean Thematic Centre; PI, principal investigator; PML, Plymouth Marine Laboratory; QC, quality control; SOCAT, Surface Ocean CO_2 Atlas; SOCONET, Surface Ocean CO_2 Observing NETwork; TA, total alkalinity; TC, Thematic Centre; UiB, University of Bergen; UN SDG, United Nations Sustainable Development Goals; UoE, University of Exeter; VOS, Voluntary Observation Ship.

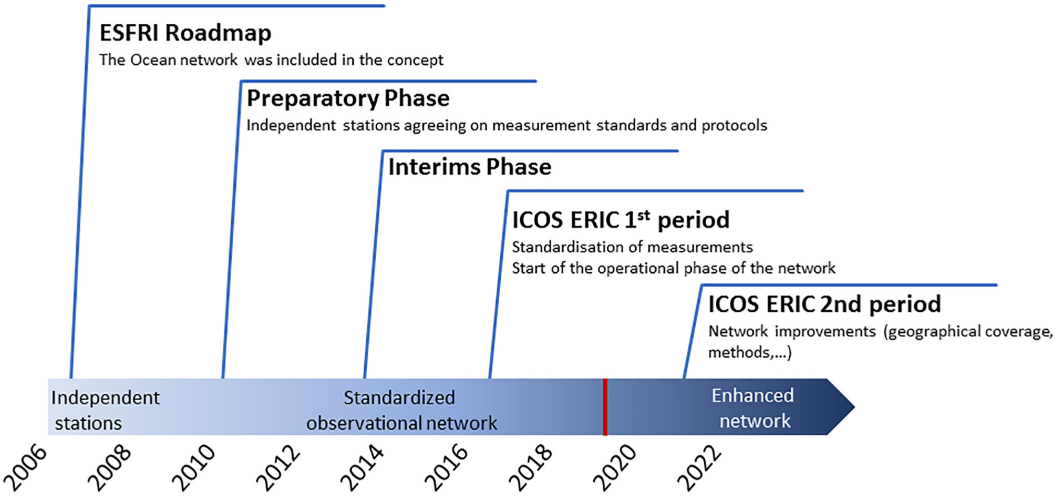

FIGURE 1 | Time line showing the development of ICOS since 2006. The red bar denotes the time of publication of this paper in the development process. It is shown how the stations developed from independent stations to an enhanced network over time (ESFRI: European Strategy Forum on Research Infrastructures; ERIC: European Research Infrastructure Consortium).

relevant TC. This operation mode is the backbone of ICOS and ensures that all data and derived products have low and clearly defined uncertainties. The three TCs are responsible for receiving the raw data and conduct initial quality control (QC). The data are then transferred to the central ICOS data repository (CP[1]).

The TCs and the CP are responsible for detailed QC of data, further processing, analysis, and delivery of products (e.g., maps, fluxes, etc.). An important aspect of ICOS is the commitment of the member states to the sustained operation of the stations in order to secure the long-term operation of the pan-European network and the value of their investment. This is of paramount importance for time series environmental observations (Henson, 2014).

The sensitivity of the oceanic carbon fluxes and reservoirs to atmospheric and ocean changes (Watson et al., 2009; Landschützer et al., 2017; Fröb et al., 2019) pushes the need to reduce the uncertainties in the observational data. Increasing the number of observations and their geographical coverage will improve derived products (Rödenbeck et al., 2015). Even if it is well-known that the carbon cycle shows annual and decadal variability, not all drivers are fully understood. The Global Carbon budget 2018 (Le Quéré et al., 2018) reports a carbon budget imbalance of 0.5 $GtCyr^{-1}$. The ICOS-Oceans network is operating with this in mind, thus concretely responding to a few indications coming out from the last OceanObs'09 conference (Borges et al., 2009; Monteiro et al., 2009). The Oceans network is managed and coordinated by the OTC, which is co-hosted by Norway (NORCE Norwegian Research Centre and the University of Bergen (UiB)) and the United Kingdom (National Oceanography Centre (NOC), University of Exeter (UoE), and Plymouth Marine Laboratory (PML)). The roles of the OTC are split between these two countries (see **Table 1**). The OTC's tasks also include the production and implementation of a roadmap,

[1]https://www.icos-cp.eu/

TABLE 1 | OTC member institutes and associated function, NORCE: NORCE Norwegian Research Centre AS, Bergen, Norway; UoE: University of Exeter, United Kingdom; UiB: University of Bergen, Norway; PML: Plymouth Marine Laboratory, United Kingdom; NOC: National Oceanographic Centre, Southampton, United Kingdom.

Role in OTC	Institution
Leadership	Shared between NORCE and UoE
Data management and data quality control	UiB
Labeling	SOOP: NORCE with contribution from UoE FOS: NORCE with contribution from PML*
Training and technical support	NORCE
New technology and new platforms and ship liaison	NOC

**PML might join the OTC at a later point.*

refreshed annually, aiming to help the MSA to maintain a robust and optimally structured network. The OTC reports to the MSA and ICOS Head Office (HO) via the "Annual Activity Report."

The institutes hosting the OTC have significant experience in marine carbon measurements, ocean climate science, and data management, gained over many years of active research and matured over the last 10 to 15 years with their participation and leadership in prominent EU funded projects (CAVASSOO, CARBOOCEAN, CARBOCHANGE, Euro-Sites, FixO3, AtlantOS, RINGO, BONUS INTEGRAL). A significant number of measurement stations were designed and developed as part of these projects, allowing a benchmark of high quality to be set. Since it is the first time that a marine network has been designed with a long term perspective, the specific protocols for running an ICOS station will be adjusted over time and will be published on the OTC's website for maximum transparency. Two motivations for designing and further evolving the ocean network have been formulated:

1. Quantifying CO_2 (and other GHG) fluxes between the ocean and the atmosphere.
2. Assessing drivers and variability of CO_2 and other GHGs in marine environments.

As to (1), highly accurate measurements of surface water pCO_2 are required, measured onboard SOOP lines and at FOS. To properly address motivation (2), additional variables need to be measured (including, but not necessarily limited to, temperature, salinity, inorganic carbon, and oxygen) both at and below the ocean's surface. This is best achieved by FOS. These two challenges, and their impact on the process of station labeling, are described below. Currently, ICOS-Oceans is concentrating on CO_2 observations, but is keeping the possible implementation of non-CO_2 GHG measurements, such as N_2O and CH_4, in mind. Such measurements are already conducted at a few stations.

As illustrated in **Figure 2**, the marine network covers the Arctic Ocean including the Barents Sea, the North and sub-tropical Atlantic, the Baltic Sea, and the Mediterranean Sea. One line also periodically covers the Southern Ocean. The network currently includes 11 SOOP lines, 9 FOS, and one MFT station, which consist of both a FOS and an ecosystem tower.

All measuring stations highlight the importance, significance, and connection of the ICOS-Oceans network to global ocean observational efforts. **Figure 3** shows the observational capability of the network and its relevance to the international framework. The necessities highlighted by the international marine observations community are also indicated.

THE OCEANS NETWORK

The Oceans network consists of three entities. The first is the OTC, which is an ICOS central facility and functions as the coordinating body, designed to assist and support the station PIs with their ICOS-related work. The second is the ocean MSA which is the station principal investigator's (PI) decision body. The third is the observational stations themselves.

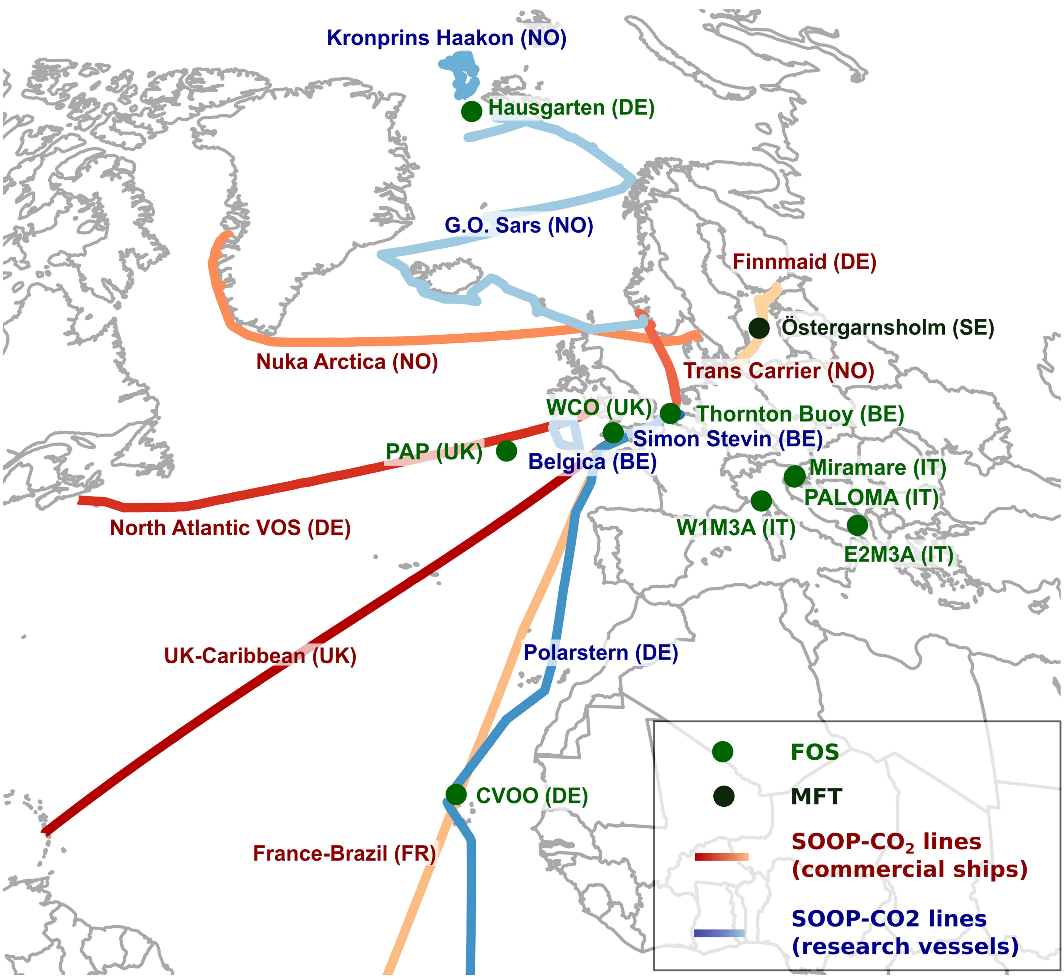

FIGURE 2 | Distribution of stations and coverage of ICOS-Oceans network as in February 2019. Please note that ICOS-Oceans is a developing network. Please find a complete and up to date station list and information about the stations in https://otc.icos-cp.eu/station-network.

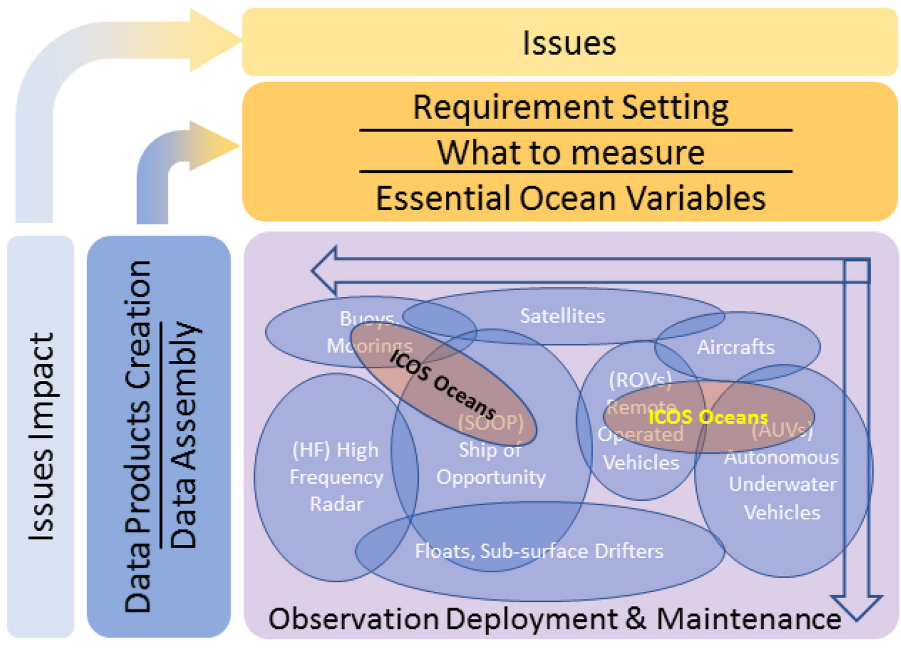

FIGURE 3 | Observational capacity and capability of ICOS in relation with the Global Ocean Observing System (GOOS) Framework for Ocean Observing process (figure was adapted from GOOS; Lindstrom et al., 2012). The black label indicates the current capability of ICOS, and the yellow the future potential (see section "Emerging Technologies").

The OTC is responsible for supporting the network of marine observing platforms, in collaboration with the CP and the ICOS HO, to deliver the data needed to quantify the role of the ocean in the global carbon cycle and any changes in this. The six major tasks of the OTC are:

(1) *Coordination of the marine network and network design.* The OTC facilitates forums for communication between the partners, e.g., regular newsletters and information exchange with the marine MSA, and also promotes communication with partners outside the network, e.g., stakeholders, external projects, other research infrastructures, and external data users [such as the Global Carbon Project, the International Oceanographic Data and Information Exchange (IODE) of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, Copernicus, the European Marine Observation and Data Network (EMODnet), and the Surface Ocean CO_2 Reference Observing Network (SOCONET)] (Wanninkhof et al., 2019). This ensures wide visibility and use of ICOS data, and enhances the scientific and social relevance of both the Ocean network and ICOS in general. The OTC will also produce and implement a roadmap aimed at helping the MSA to build a robust and optimally structured network. The roadmap will be refreshed annually and be reported on to the MSA. All OTC efforts are reported in the OTC annual activity report.

(2) *Training and knowledge exchange.* The OTC is responsible for providing training to optimize and standardize the performance of the network, and to promote the exchange of knowledge. The major training activity is an annual workshop, which represents an important meeting point between the instrument suppliers, station PIs and technical staff, and data managers.

(3) *Station labeling.* The OTC is responsible for both the formal application and data evaluation of the ICOS marine stations. The process is started by applying to become an ICOS-Oceans station. In this first step (see section "Labeling"), the station design is evaluated and the outcome is discussed between the OTC and the station PI. The work toward labeling the stations involves automatic data reduction and QC using state-of-the-art software (QuinCe) developed at the OTC, manual evaluation of the automatic data QC, and the writing of a labeling report on which the ICOS GA bases its decision of whether or not to accept a station into the ICOS network.

(4) *Data quality control and management.* The OTC operationally produces data streams of the Essential Ocean Variable "Inorganic Carbon," the core variable of the marine part of ICOS, operational and available through the CP. This is a pivotal mission of OTC and a major undertaking due to the variety of analytical instrumentation used by the marine network. Automated data ingestion, processing, and QC software has been developed by OTC.

(5) *Ship Liaison.* The OTC has begun a systematic program of engagement with the shipping industry/coastal installations community, with the aim of operating autonomous data collection systems focused on evaluating CO_2 fluxes and other GHGs across the air-sea interface.

This effort can also support the SOOP community in sustaining and replacing platforms, in particular SOOP lines, via dialog with the shipping industry.

(6) *New technology and new platforms*. The OTC will encourage collaboration with technology partners in future research grants to identify and exploit new sensors and new platforms.

The OTC is also responsible for developing best practice guidelines and protocols to ensure the high quality of ocean carbon data. The ambition is to provide near realtime (NRT) data, which will be used to assess the oceans' role in the global carbon cycle and the uptake of GHGs. Furthermore the OTC advocates ocean carbon science in policy and to funding bodies, and speaks for all ICOS ocean stations. It operates in close contact with the MSA chairs to ensure that the needs of the observational community are met. It also represents the ICOS stations in the European and international ocean carbon community.

The MSA consists of all the station PIs, and its main remit is monitoring, developing, and improving the scientific and technical basis of the network. The MSA, together with the OTC, have formulated the operational requirements for the stations, following Standard Operating Procedures (SOPs) established by the marine inorganic carbon chemistry community (Dickson et al., 2007) and adapting them to the network needs where necessary.

Each observational station has its own scientific focus. Most stations existed before ICOS and were established by scientists not only to monitor carbon fluxes, but also to study major marine biogeochemical cycles and their governing processes. This is one of the main strengths of ICOS, as it ensures that the members of the MSA (with its pure observational focus) are also well-connected with the scientific community. Another implication is that ICOS stations can serve as multidisciplinary observational platforms for further research and as validation stations for the development of new observational strategies.

The three entities together provide highest quality data for surface ocean pCO_2. The data shown in **Figure 4** are from 2017, where the ICOS SOOP network produced nearly 1 million data points in the area north of 30°N. Data gaps due to instrument failure or just lack of SOOP lines (e.g., Mediterranean) are clearly visible. ICOS will help the community to reduce data gaps and establish more SOOP lines to fill the white spots on the ocean map.

Structure and Operation of the Observational Stations

ICOS-Oceans network includes different types of stations measuring various parts of the marine carbon cycle. Some are contributing to the observation and documentation of air-sea fluxes of CO_2 whilst others also add to the understanding of flux variability and its drivers. Presently the core variables for SOOP lines are sea surface pCO_2, intake and equilibrator temperature, air and equilibrator pressure. For the FOS, the core variables are pCO_2, sea temperature, salinity, and dissolved oxygen. Stations providing these variables with the specified accuracy (an up-to-date version of the ICOS-Oceans labeling document can be found at https://otc.icos-cp.eu) will be classified as "Class 2" stations. If a station provides additional variables (e.g., dissolved oxygen, a second carbon variable) then it can become a "Class 1" station. It is important to mention that both station classes produce the same quality of data. The classification exists in order to highlight to which extent the station, in terms of the variables that it measures, is able to provide the information needed to understand either motivation 1 (for SOOP) or motivation 2 (for FOS), or both.

The requirements are subject to regular revision, recognizing that technical and scientific developments may lead to higher quality measurements, or the measurement of new variables. Independent of the platform, all ICOS data require comprehensive metadata. This is overseen by the OTC to ensure the reliability of the measurements and thus the highest quality data are collected.

Ship of Opportunity Program

In the past, the terms VOS and SOOP were both used for surface water carbon measurements onboard ships. To differentiate clearly between the meteorological observations (VOS) and the work that is done in ICOS, we use the term SOOP. The SOOP stations include commercial ships and research vessels that are equipped with a pCO_2 measurement system and auxiliary sensors (seawater temperature, salinity, meteorological sensors). It is worthwhile noting that the accuracy requirements for all required variables are identical for both station classes. For CO_2 determination, all of the SOOP stations are equipped with systems that use the same principle: determination of pCO_2 in air that is in gaseous equilibrium with a continuous stream of seawater. The maximum level of uncertainty is set to ± 2 μatm. This methodology follows international standards (Dickson et al., 2007), ensuring the lowest uncertainty currently achievable. Data reduction techniques follow the requirements of the international community effort (SOCAT; Pierrot et al., 2009; Pfeil et al., 2013; Bakker et al., 2016).

The data from the SOOP network primarily contribute to motivation 1 (CO_2 flux quantification), whilst in conjunction with satellite and re-analysis data, they can contribute to main motivation 2 (drivers of flux variability).

Requirements for an ICOS marine SOOP Station include:

1. Calculation of fCO_2 based on measured xCO_2 and following an approved method and SOP criteria (Dickson et al., 2007).
2. Making quasi-continuous CO_2 measurements, not analyses of discrete samples.
3. Using a flow-through equilibrator system to measure xCO_2 in its headspace gas.
4. That QC, equivalent to the two highest SOCAT QC flags (fCO_2 accuracy better than 2 μatm), is deemed acceptable and includes cross-over analysis where possible (Pfeil et al., 2013; Wanninkhof et al., 2013).

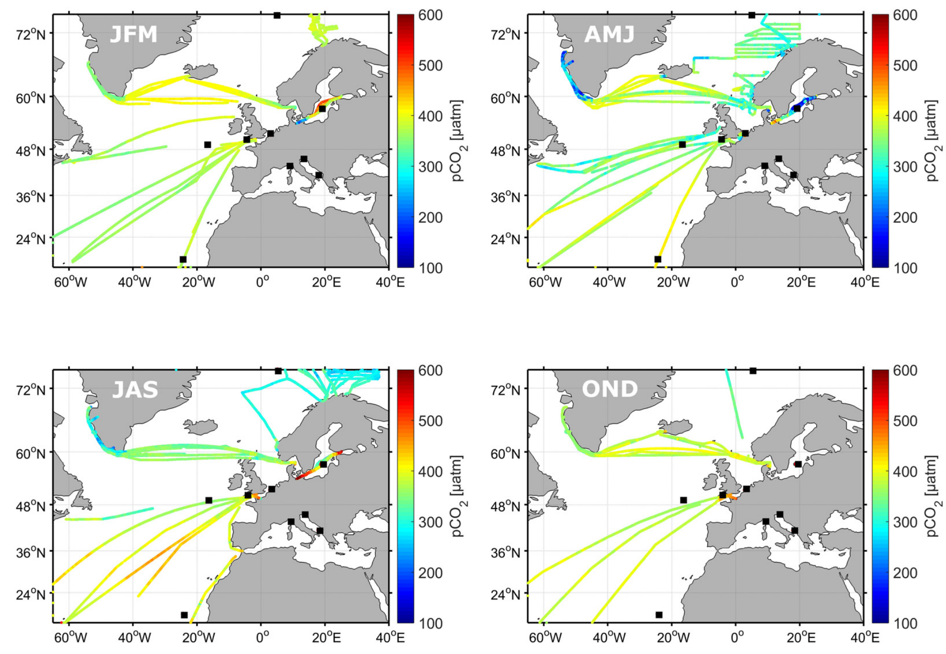

FIGURE 4 | Seasonal pCO_2 (e.g., JFM: January, February, March) data generated by the ICOS SOOP network in the year 2017 (data can be downloaded at www.socat.info). The FOS are shown as black squares.

Furthermore, metadata are required to be submitted with the data, including:

1. Region and time of measurements.
2. Proof of the calibration of the CO_2 measurements by regularly measurement of at least two non-zero gas standards traceable to World Meteorological Organization (WMO) standards.
3. Description of core variable calibration including regular recalibration of different sensors used.

On one of the SOOP lines of the network (Baltic SOOP, Baltic Sea), continuous measurements of surface methane partial pressure is established using detection by off-axis cavity enhanced output spectroscopy (Gülzow et al., 2011, 2013), serving as a pilot study for the network.

Fixed Ocean Stations

The FOS include open ocean stations (they might be reasonably close to the coast but are far enough away, and in sufficiently deep water, that coastal interaction is not significant), coastal stations, and benthic stationary platforms. *In situ* pCO_2 sensors, which are commercially available and based on membrane equilibration technology, are most commonly used here. Alternative options that include calibration gases and a different equilibration method are limited, and none of the ICOS FOS stations are equipped with such in 2019. A number of studies and intercomparison exercises indicate that the systems presently in use are not as stable as those used for the SOOP stations, and for this reason the pCO_2 performance criterion has been relaxed to $\pm 10\ \mu atm$. As for SOOP, two station classes have been defined for FOS.

A FOS usually consist of a surface buoy with attached instruments or sensors performing continuous carbon measurements in the ocean and lower atmosphere, and/or a sub-surface mooring measuring continuously at one or more depths. FOS can also be ship-based when discrete measurements are conducted from a fixed location. Distinction between coastal and open ocean is, in addition to the distance from land, based on habitats, light penetration, nutrient availability, processes (e.g., dense water formation at the shelf and deep open ocean), tidal fronts, and river runoff. For fixed stations, inorganic carbon variables and hydrography are primarily measured, but a wide range of measurements can be performed either using discrete sampling with post-sampling analysis, or by use of autonomous sensors (e.g., Wanninkhof et al., 2013; Coppola et al., 2016), IOCCP Instruments and Sensors directory[2]). Sampling procedures follow the GO-SHIP manual for discrete data and (Hood et al., 2010; Lorenzoni and Benway, 2013; Wanninkhof et al., 2013) for sensor-based data. Some of the FOS (especially the ones that are located in the open ocean) determine pCO_2 and other variables at several depths in addition to the surface, and thus provide information of the vertical structure in the upper water column. This enables an extensive investigation of the air-sea fluxes and the drivers' variability. Thus, data from

[2]http://www.ioccp.org/index.php/instruments-and-sensors

the FOS contribute to both main questions (flux calculations and drivers of its variability).

Requirements for ICOS FOS, using discrete samples and/or continuous measurements (class 1 and class 2), include:

1. Following approved methods and SOP criteria (Dickson et al., 2007) when measuring two out of four carbonate variables (dissolved inorganic carbon (DIC), alkalinity (TA), pH, and pCO_2).
2. Proving *in situ* calibration of pCO_2 by measuring at least one non-zero gas standard traceable to WMO standards, or, at minimum, discrete samples at the start and end of deployment.
3. Performing an appropriate secondary QC [for example GLODAPv2, SOCAT, alkalinity-salinity relationships, multi linear regression (MLR)].

Furthermore, required metadata need to be submitted with the data, including:

1. The documentation of regular calibration of the instruments.
2. A complete description of core variable calibration.
3. A detailed description of sampling and sample handling.

As of 2019, the main observational platforms of the ICOS network are SOOP lines and FOS. Two other approaches (direct flux measurements and repeat hydrography sections) are under development. While the direct flux observations are close to being included into the ICOS data flow, the inclusion of the repeat sections is still under discussion.

Marine Flux Towers

Direct flux observations deliver directly to motivation 1 ["Quantifying CO_2 (and other GHG) fluxes"] of the ICOS network motivation. While SOOP and FOS stations calculate the CO_2 flux based on the pCO_2 difference between the atmosphere and the ocean, micrometeorological measurements using eddy covariance (EC) data are based on a direct measurement of vertical gas fluxes, but the stations and data need careful QC for reliable estimates (McGillis et al., 2001; Rutgersson et al., 2008). The prerequisites for EC measurements in marine environments are somewhat different than in terrestrial environments, and thus special labeling is required that will need an exchange of expertise between the ocean and ecosystem domains. Flux towers are predominantly situated on shores or in near-shore regions, with varying degrees of terrestrial influence. Data from different stations will therefore be grouped according to the expected level of terrestrial influence:

1. Group 1: Flux footprint represents open-sea conditions, and land influence is limited to conditions with meso-scale circulation systems (e.g., upwelling, sea-breeze circulation).
2. Group 2: Flux footprint represents "coastal zone" with heterogeneous properties.
3. Group 3: Flux footprint represents shore area and is highly active in terms of the carbon cycle.

Flux measurements can also be performed on ships, but this requires additional analysis of motion correction and flow distortion (McGillis et al., 2001; Miller et al., 2010; Landwehr et al., 2014; Prytherch et al., 2015; Butterworth and Miller, 2016). If EC data taken from moving ships are to be introduced in ICOS, a common methodology for motion correction will need to be developed. At current, only one EC flux tower is maintained within the ICOS-Oceans network, which is located on the island of Östergarnsholm in the central Baltic Sea.

Requirements for ICOS marine flux towers (MFT) (class 1 and class 2):

1. Stations should be visited on a regular basis (monthly) and instrumentation must be cleaned.
2. For stations with high salinity and large amounts of sea spray, the CO_2 flux-system signal should be dried. For a non-dried system, station PIs should provide data showing this is not necessary.

Furthermore, metadata need to be submitted with the data, including:

1. A description of flux system calibration.
2. Details on data processing, required corrections, and quality.

Repeat Sections

Discussions are currently underway to incorporate these invaluable data into ICOS, and the OTC is working toward making data from repeat hydrography sections (e.g., GO-SHIP, Sloyan et al., 2019, this issue) available to the marine network for validation and verification purposes. Repeat sections are performed at least once per decade using research ships equipped with advanced high precision systems, in particular, following Dickson et al. (2007) for seawater CO_2 chemistry analyses. These are typically conducted on-board on water samples collected with a CTD rosette, and sampling covers the full depth of the water column. This allows accurate measurements of carbon and transient tracers, such as CFC-12 and SF_6, required for the estimation of contemporary and anthropogenic carbon storage and transport. Calibration of the measurements is performed using reference material as described by Dickson et al. (2007). Criteria for data analysis shall follow the GO-SHIP manuals (Hood et al., 2010), and crossover analyses are useful for verifying the accuracy of the data (e.g., Key et al., 2015; Olsen et al., 2016).

Data from repeat hydrography sections would clearly contribute to the main motivation 2.

The proposed requirements for ICOS marine repeat sections include:

1. Following approved methods and SOP criteria (Dickson et al., 2007) when measuring two out of four carbonate variables (DIC, TA, pH, pCO_2).
2. The provision of complete metadata, including description of core variable calibration.
3. Proving regular calibration of the instruments.
4. Covering full depth of the water column.
5. QC control performed, equivalent to secondary QC routines in GLODAPv2 (Olsen et al., 2016).

LABELING

One of the fundamental aims of the OTC is to bring the European marine station network to an operational state with fully standardized and verified procedures throughout. While the community has agreed upon a set of SOPs that outline how specific measurements should be conducted with a required accuracy, and procedures for data reduction (Dickson et al., 2007; Pierrot et al., 2009), it has been largely a matter of trust that each station is implementing them to a sufficient standard. The ICOS station labeling ensures that each station is built and maintained to the specifications defined in the labeling documents and thus following internationally agreed SOPs, which is the basis for producing high quality data sets in the future.

The basic process of the station labeling is illustrated in **Figure 5**. The very first step in becoming an ICOS station is that the national network suggests the station to focal point of the national ICOS network. This is an important step, as the participating member state needs to cover the cost of the station contribution for participation in ICOS. The next step is based on the metadata for the station, collecting details of the instrument's construction, the sensors used, and the maintenance and calibration schedule of the instruments. These assessments ensure that the station is capable, at least in theory, of producing data of the quality required by ICOS. If a station does not meet these requirements, ICOS OTC provides advice on the improvements needed in terms of physical changes to the instrument and/or operating procedures.

Step 2 of the labeling process involves examining the data themselves. The station must provide at least 4–6 months of raw data (as it is collected from the instrument, with no processing performed). This is processed by an OTC expert using standardized data reduction and QC tools (see section "Data Life Cycle"). The results are examined to identify poor data that indicate either that the instruments are poorly configured or are excessively vulnerable to failure. This involves extensive interaction with the station PIs to maintain full transparency of the assessment process and to ensure that the characteristics of each station are fully understood to avoid unusual-looking data being falsely flagged as being of poor quality. If an unacceptably large proportion of the data is deemed to be of bad quality, the OTC and station PIs will enter discussions to determine how to best improve their instruments and installation and therefore increase the data reliability to the required level. Once the changes have been made, a further period of data (of a length determined by the seriousness of the problem and the minimum volume of measurements required to be satisfied that the issue has been resolved) must be submitted and examined before the station can pass step 2.

Once both labeling steps have been passed, the station's details are passed on to the ICOS GA for official registration as an ICOS station. All 21 ICOS-Oceans stations passed Step 1. Currently eight stations are in Steps 2 and 5 are labeled ICOS stations after they passed Step 3. For updated information about the labeling process please see https://meta.icos-cp.eu/labeling/.

Examination of ICOS stations does not stop once labeling is complete. Every data set submitted to ICOS by a station is checked by an expert within the OTC to ensure that the quality of the data is being maintained. The hostile environment in which oceanic stations operate means that short-term periods of poor data and instrument failures are inevitable, but the expert reviews can help identify issues that may or have become longer term issues. Advice on the best way to mitigate these issues can also be provided. This can be aided by communication and knowledge sharing between stations across the whole network, facilitated and encouraged by OTC. The OTC will also continually ensure that stations are adhering to the recommended maintenance and calibration schedules.

Data Life Cycle

Labeled stations submit their data to ICOS where they are processed using a standardized workflow. This ensures that all data are subjected to the same community-approved processes and QC routines to produce consistent and fully reproducible outputs for all data. This workflow is shown in **Figure 6**, and described in detail below.

Data processed through ICOS OTC go through the data lifecycle in a number of stages, each of which is referred to as a different level. Raw data taken directly from instruments (before any processing is performed) is termed Level 0. They are submitted to the OTC using QuinCe, an online data processing and QC tool developed by OTC, and data are immediately archived in the CP. All data are archived at each stage of processing to ensure full provenance, traceability, version

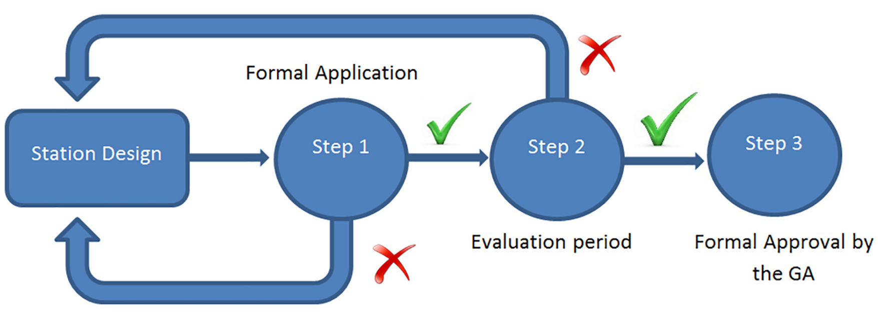

FIGURE 5 | ICOS labeling process. This process is common for all domains. Green ticks indicate that the step is successfully completed, while red crosses indicate that there are issues that need to be addressed before proceeding to the next step.

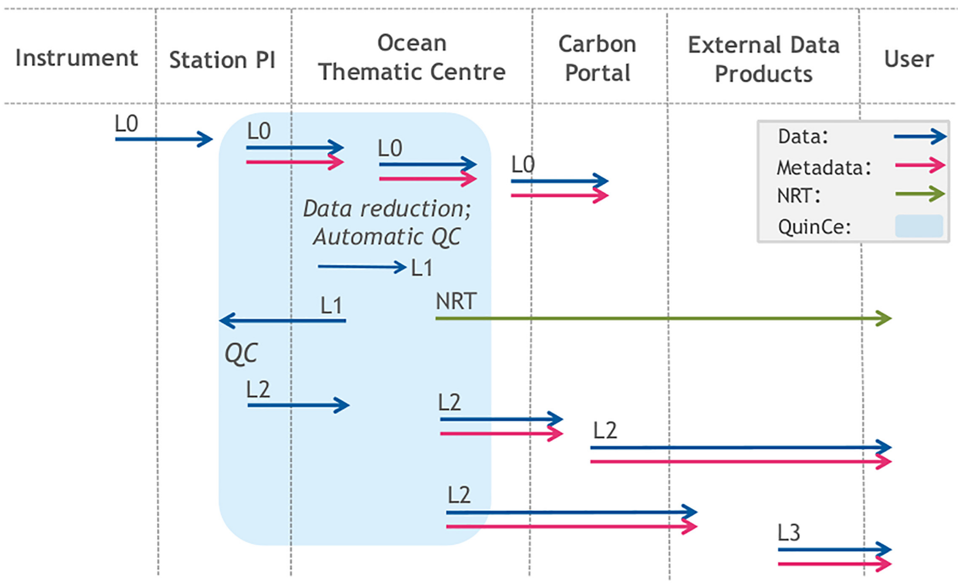

FIGURE 6 | ICOS OTC Data life cycle, showing flow of data (blue arrows) and metadata (red arrows) between instrument, station PI, OTC, CP, producers of external data products, and final users, for Level 0 through 3 and NRT data. The processes in which the automated data QC and data reduction technique QuinCe is involved, is shown as a light blue shading.

control, and compliance with FAIR data treatment practices (Wilkinson et al., 2016):

Findable:

F1. (meta)data are assigned a globally unique and eternally persistent identifier.
F2. data are described with rich metadata.
F3. (meta)data are registered or indexed in a searchable resource.
F4. metadata specify the data identifier.

Accessible:

A1 (meta)data are retrievable by their identifier using a standardized communications protocol.
A1.1 the protocol is open, free, and universally implementable.
A1.2 the protocol allows for an authentication and authorization procedure, where necessary.
A2 metadata are accessible, even when the data are no longer available.

Interoperable:

I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.
I2. (meta)data use vocabularies that follow FAIR principles.
I3. (meta)data include qualified references to other (meta)data.

Reusable:

R1. meta(data) have a plurality of accurate and relevant attributes.
R1.1. (meta)data are released with a clear and accessible data usage license.
R1.2. (meta)data are associated with their provenance.
R1.3. (meta)data meet domain-relevant community standards.

QuinCe then performs all necessary data reduction calculations according to internationally agreed standards (Dickson et al., 2007; Pierrot et al., 2009), and automatic QC to identify potential problems in the data. The resulting Level 1 data are also sent to the CP to be archived, and also published as NRT data, allowing early access to the data for users with time-sensitive data needs (full access to the NRT data will be provided on request with the understanding that they have not been fully quality controlled and may contain errors). For those stations that transmit data in real time to shore, this process from Level 0 upload to Level 1/NRT will be fully automated, providing the fastest possible data availability while simultaneously reducing the workload of the PIs.

The Level 1 data are further quality assured and controlled by the station PI's, who can accept or reject the results of the automatic QC and perform their own additional QC using their expert knowledge of the characteristics of the carbon system measured at their station. The QCed data will be sporadically checked by the OTC in order to guarantee the high quality of the ICOS data. This will involve extensive dialog with the PI to understand the specific nuances of their data. Once the OTC expert is satisfied, they submit the fully processed data to the CP for final publication as Level 2 data. After this step has been fulfilled, the Level 1 data are no longer accessible through the standard data access interfaces, but remains in the archive for traceability.

The published Level 2 data sets are incorporated into data products (e.g., SOCAT, or the Global Carbon Budget by the Global Carbon Project; Le Quéré et al., 2018), and will be used toward the motivations stated earlier. Furthermore, the data can be used in further scientific research (e.g., as input to, or ground truthing of, models or satellite observations). The ICOS CP provides facilities for publication of 'elaborated' data products, such as flux maps, as Level 3 data, with full provenance links back to the original Level 2 datasets to ensure that proper credit is given to the original data providers. Users creating these Level 3 products are able to contact the PIs through the OTC to discuss aspects of their data sets and to report any possible problems with the data that may need to be corrected. This dialog allows Level 2 datasets to be corrected accordingly and new versions published.

ADDED VALUE OF THE ICOS-OCEANS NETWORK

Network Optimization

The ICOS-Oceans network is already established in a very wide spectrum of marine environments, from the very active and diverse coastal regions to open ocean areas (large reservoirs), but also from polar areas to equatorial environments. This already provides a good and solid backbone for the network, as it allows fulfillment of the motivations of the network and additionally allows studies on the sensitivity of large carbon reservoirs and ecosystems to anthropogenic forcings and to changing conditions.

However, it needs to be acknowledged that most of the ICOS-Oceans stations have been operating prior to the formation of ICOS and that they were established for project-related research, and hence generally only have finance funded for the duration of the project(s). However, this financial and operational model is not sustainable. On top of that, the geographic distribution of the network is based on the nations that have signed up to the ICOS ERIC, and additionally on each nation's decision on which station(s) to nominate. Such a distribution might not be in full accordance with the ICOS-Oceans network's main motivations (see section "Introduction") and hence the preferred spatial coverage. In reality these are not optimal conditions for network design. However, the existing network is functional and possesses a great degree of integration and operational capacity. For the latter, significant credit has to be awarded to the determination of the European Marine Carbon Observation community that has built upon the achievements of many EU and nationally funded research projects and advocated for the inclusion of ocean observations in ICOS.

It also needs to be recognized that one of the strongest features of ICOS is that it was developed within the ERIC platform. Within this framework, each member state is committed to support the high quality operation of stations over a long period (each country is free to determine the support level for its stations). To make this possible, a number of stations were overhauled and upgraded so that they can operate according to the ICOS standards. This fact, in conjunction with the structure of ICOS (interaction between HO, Research Infrastructure Committee, GA), gives the opportunity for the networks (domain, national) to have an additional communication line with the funding agencies, highlighting successes and advocating their needs. In this way, national funding bodies can have a more integrated view of the network, realize its operational status and identify its strengths and possible bottlenecks. This also allows funding bodies to evaluate more efficiently the importance of a strategic design of a research observation network and gain feedback of the added value obtained by their commitment and investment.

The network can benefit from a direct link between its governing and operational bodies (i.e., the station PI's and the stake holders). Tools like integrated data analysis, use of modeling products, and assessment of new technologies (e.g., intercomparison exercises, new platforms, see section "Tools for Network Development") will highlight geographical and operational gaps and can suggest where best to distribute and allocate resources.

On a more practical and technical level, the development of tools like QuinCe (see section "Data Life Cycle") strengthens this even more and enables automatic submission of data to the ICOS CP (and thus other data activities, e.g., SOCAT, Global Carbon Project). This will reduce the effort and time needed to publish datasets, and the ability to accept and automatically process near-real-time data and additionally assist in the identification of technical issues with the station. Streamlining these processes is becoming ever more important as demand for high quality, near-real-time climate data grows. Both OTC data engineers and station PI's are actively involved in the QC process throughout the data lifecycle and constantly evaluate both a station's performance and providing feedback for QuinCe.

Stronger Community Voice and Impact

ICOS provides the opportunity for the European marine carbon community to strengthen communication lines with marine science policy and with decision-making bodies, and maximizes the societal impact of the network. This is achieved through interaction with ICOS bodies including a dedicated ICOS communication service.

The operation of the CP and the dissemination and publication of data in a large, globally visible, open access database multiplies its scientific impact.

It is expected that ICOS-Oceans will have a central role in shaping a sustained global marine carbon system and GHG observation network. ICOS OTC has a leading role on the discussions to harmonize data formats and data QC, and ensures that metadata requirements are aligned with international activities such as the NOAA Ocean Acidification Program, SOCAT, and the United Nations Sustainable Development Goal 4.3 on ocean acidification.

Integration and Collaboration Across the ICOS Domains

ICOS is one of the first Environmental ERICs to be established and one of the few that covers all environmental domains. To a great extent this is a response to society's demand for better and more reliable information on the carbon cycle. ICOS wants to achieve this via observations in all three domains (oceans, atmosphere, and terrestrial biosphere) and stimulating interaction and synergies between them. In particular, the enhancement of cooperation between the oceanic, atmospheric, and terrestrial ecosystem domains and research groups within ICOS and consequently throughout Europe will result in more robust scientific results and help to identify gaps in carbon budgets (e.g., Le Quéré et al., 2018).

The three domain networks are already operating under the same basic principles (structure, labeling, data policy), highlighting the integrated nature of the network. Furthermore, the domain TCs have already identified scientific and operational areas for enhanced collaboration and integration. Some examples are the supply of high quality CO_2 reference gases by the ICOS central calibration facility (CAL) to the ocean network, attempts to perform high quality atmospheric measurements on-board SOOP stations (currently tested through collaboration between the Oceans Network and the ICOS ATC), and the assistance and knowledge exchange between OTC and ETC on EC measurements at coastal stations, which can potentially evolve into high quality direct CO_2/GHG fluxes calculation on-board SOOP lines.

Additionally, the next integration level will be to identify more synergies and interaction between the stations of different domains. An example might be to cluster a coastal FOS, an atmospheric mast, and an EC tower, which are all located within a specific distance, and attempt to identify boundaries and footprints, and combine/compare measurements and fluxes.

ICOS-Oceans in the International and European Ocean Observations Landscape

To our knowledge, ICOS is one of the few networks (if not the only one) that has accrued a status as a legal entity. ICOS-Oceans represents an active part of the marine carbon community and is therefore strongly involved in established groupings, efforts, and actions, such as SOCAT, GLODAP, and GO-SHIP. It builds upon the existing research effort and strives toward harmonizing methodologies and practices. Within that spirit there is ongoing dialog between ICOS-Oceans and international ocean observational groups such as the SOCONET, the Global Ocean Acidification Observation Network (GOA-ON), and the Global Ocean Observing System (GOOS, EuroGOOS).

The ICOS OTC also cooperates with the International Ocean Carbon Coordination Project (IOCCP) on the strategic design and coordination of activities to facilitate the evolution and enhancement of globally acceptable strategies, methodologies, practices, and standards for marine carbon research.

On the European level, ICOS is a strong member of the ENVRI community. Within ENVRI, synergies between the research infrastructures can be identified, and cooperation and collaboration between networks can be established. More specifically, there is ongoing and fruitful interaction between ICOS-Oceans, EMSO, Euro-ARGO, and LifeWatch, both in terms of co-location of stations and the exchange of scientific and technological expertise and data management methodologies. ICOS-Oceans follows the developments of initiatives and projects such as JERICO, DANUBIUS, and LTER, but also communities like FerryBOX in order to maximize cooperation and identify complementing scientific and operational pathways.

Integrated Carbon Observation System is active in the Group of Earth Observations (GEO) initiative, hence there is an opportunity for the ICOS-Oceans and the marine carbon research community to promote its own ocean carbon programs and activities for inclusion into globally integrated Earth system observing networks.

TOOLS FOR NETWORK DEVELOPMENT

Evolving Network Design

In order to respond adequately to the motivations of ICOS-Oceans (see section "Introduction"), an optimal network is needed. As mentioned in Section "Added Value of the ICOS-Oceans Network," the ICOS-Oceans network is based on an opportunistic approach and the willingness of countries to contribute to such a network. The network needs to be improved with regard to its spatial and temporal coverage and additional variables should be considered for inclusion. Obvious improvements are additional SOOP lines (e.g., in the Mediterranean Sea) to improve spatial resolution. An important step forward will be the development of a carbon flux map for the European shelf seas in order to both identify any existing gaps in the network and regions that are overdetermined and that might be used as reference regions. These data can also be evaluated for use with atmospheric inversions (e.g., Rödenbeck et al., 2015). At least each biogeochemical Province (Longhurst, 2007; Oliver and Irwin, 2008) should be covered by a FOS. Furthermore, additional variables should be included in the future. These could be variables that give additional information about the carbon system [e.g., discrete sampling on SOOP, $\delta^{13}C(CO_2)$ measurements], or variables that allow a broader understanding of the marine system (e.g., N_2O, CH_4, nutrients) in certain regions. Additionally, the ICOS HO is active on the expansion of the network in all domains and works closely with all TCs to identify network gaps, hotspots, and expansion opportunities. It needs to be mentioned that OTC is targeting scientific groups and communities, while the HO can be more influential on funding bodies.

Emerging Technologies

The adoption of new technology is necessary to continuously improve the network and to future proof it. This includes additional observational approaches (e.g., direct flux measurements, see above) and novel instrumentation. The basis of the network was designed by the community through ICOS PIs. Emphasis was given to the quality of the measurements and the robustness of the observational methodologies, and these are the main criteria for selecting specific instruments and setups. The OTC and the MSA are investigating developments in analytical technology and measurement practices, in order to identify when new systems are reliable and suitable for their implementation in ICOS stations.

It is also evident that the inclusion of continuous, frequent, and reliable data for all relevant carbon variables is desirable for the ICOS-Oceans network and has been endorsed by the OTC, the HO and the CP. Currently, the instrumentation for pCO_2 measurements can be considered mature and readily available (Pierrot et al., 2009). For *in situ* pH determination, the technology is becoming more mature, with commercial sensors and systems becoming available (Martz et al., 2010; Bresnahan et al., 2014; Rérolle et al., 2018). It has yet to be proven that these sensors fulfill the tight criteria required for using pH data to constrain the marine inorganic carbon system over the long deployments that are typical at the ICOS-Oceans stations. Analytical systems for *in situ* determination of DIC and TA are gradually being developed (Li et al., 2013; Wang et al., 2015) with the promise of elevated reliability in the near future (up to 5 years). Additionally, the technological development of the next generation of laser-based detectors is maturing, and their integration into alternative observational platforms such as ASVs, gliders, and profiling floats (Fiedler et al., 2013) is planned. Such new platforms and innovations will complement and enhance the current network by increasing spatio-temporal coverage and fill important data gaps. It is important to stress that the ICOS-Oceans network is perfectly suited to evaluate these sensors by providing established platforms delivering high quality carbon data.

Strengthen Engagement With the Marine Industries

The success of the ocean observing system relies on collaboration with and engagement by the marine industries. Half of the ICOS SOOP stations are located on commercial ships, so it is self-evident that the relationship with the maritime industry is a priority. There is a specific role for this activity within the OTC (a maritime industry liaison officer is located at NOC, United Kingdom), so that this collaboration is enhanced. Planned activities include meetings between the active members of the ICOS-Oceans observing community and the marine industries, with the aim to further strengthen and expand the network. At the same time, the marine industry landscape is evolving, with new infrastructures being developed (e.g., wind farms, ocean energy parks). Thus, it is beneficial to all parties to promote collaboration and synergies between the oceans network (especially coastal fixed stations) and operating companies.

CONCLUSION

The ocean component of ICOS is the first multi-national effort within the marine community for standardizing marine CO_2 observations from the single measurement, to data reduction, to final data products. The idea and effort in harmonizing marine CO_2 observations is not new; ICOS is formalizing this effort, with stations obliging themselves to follow agreed protocols. The compliance of the protocols is monitored by the OTC, so that problems at single stations can be identified at an early stage and necessary steps can be undertaken to guarantee the high quality of the ICOS carbon data. The common data reduction and QC tool (QuinCe) is at the final development stage, which will enhance the data QC and problem identification significantly. Already, though, it has been put into action and as a result 5 stations have completed step 2 of the labeling procedure and received official ICOS Class 1 status.

The network is constantly evolving, and an important part of this is to reflect on the challenges and the drawbacks that came up and still need to be addressed. Issues like harmonizing the labeling procedures for different type of stations (e.g., open ocean vs. coastal) and the spatial gaps (the network in 2019 is still unbalanced to the North Atlantic Ocean) of the network (network design) are still under discussion within the ICOS-Oceans community. As a network, ICOS-Oceans has the capacity to address these challenges and find the answers to overcome them. Currently, the funding status for a number of stations is not sustainable, as the operational funds are either not adequate (or non-existent) to allow the station to operate at the ICOS high standards. But the direct connection from the station PI through the OTC to the stakeholders gives a great opportunity to secure the high scientific quality of the data and the long term stability of stations. Thus, they can serve as multidisciplinary observational platforms for further research, and as validation stations for the development of new observational strategies.

Finally, it needs to be acknowledged that, despite the challenges, the operational capacity of the network is strong. The dedication of the ICOS-Oceans PIs, the scientific and managerial competences of the OTC and the potential impact of ICOS ERIC are a good basis for its success.

AUTHOR CONTRIBUTIONS

All authors have made a substantial contribution to the data analysis, and commented and approved the manuscript. TSt, TG, BP, SL, and SJ drafted the manuscript.

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REVIEW
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Advancing Observation of Ocean Biogeochemistry, Biology, and Ecosystems With Cost-Effective *in situ* Sensing Technologies

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Advancing our understanding of ocean biogeochemistry, biology, and ecosystems relies on the ability to make observations both in the ocean and at the critical boundaries between the ocean and other earth systems at relevant spatial and temporal scales. After decades of advancement in ocean observing technologies, one of the key remaining challenges is how to cost-effectively make measurements at the increased resolution necessary for illuminating complex system processes and rapidly evolving changes. In recent years, biogeochemical *in situ* sensors have been emerging that are threefold or more lower in cost than established technologies; the cost reduction for many biological *in situ* sensors has also been significant, although the absolute costs are still relatively high. Cost savings in these advancements has been driven by miniaturization, new methods of packaging, and lower-cost mass-produced components such as electronics and materials. Recently, field projects have demonstrated the potential for science-quality data collection via large-scale deployments using cost-effective sensors and deployment strategies. In the coming decade, it is envisioned that ocean biogeochemistry and biology observations will be revolutionized by continued innovation in sensors with increasingly low price points and the scale-up of deployments of these *in situ* sensor technologies. The goal of this study is therefore to: (1) provide a review of existing sensor technologies that are already achieving cost-effectiveness compared with traditional instrumentation, (2) present case studies of cost-effective *in situ* deployments that can provide insight into methods for bridging observational gaps, (3) identify key challenge areas where progress in cost reduction is lagging, and (4) present a number of potentially transformative directions for future ocean biogeochemical and biological studies using cost-effective technologies and deployment strategies.

Keywords: *in situ*, sensor, OceanObs, ocean technology, EOVs, biogeochemistry, biology, cost effective

INTRODUCTION

The biogeochemistry and biology of the ocean play a central role in regulating climate, providing resources for humankind, and shaping the world's economy. However, over the recent centuries, profound changes, such as ocean acidification, deoxygenation, pollution, habitat loss, and loss of biodiversity, have taken place (Le Quere et al., 2010; IPCC, 2014; Yang et al., 2016; FAO, 2018; Moustahfid et al., 2018). Understanding these changes is critical for maintaining climate stabilization, marine ecosystem health (Brehmer et al., 2011), sustainability of fisheries (Pauly et al., 2002), and other societally relevant issues, thus making ocean biogeochemistry and biology observation a high research priority.

One fundamental challenge for monitoring and studying ocean biogeochemistry and biology is that oceanic signals often have high spatial (millimeters to thousands of kilometers) and temporal (seconds to decades) variability, with long-term trends that can be hidden under large short-term natural variability (Lampitt et al., 2010). The vastness of the ocean makes it economically and logistically challenging to deploy instruments to simultaneously cover both short-term variability and long-term trends in the right locations. In the coastal oceans, the limitation of *in situ* biogeochemical and biological observational nodes and assets may be even more pronounced due to larger heterogeneity inherent in these dynamic systems. For example, even for the relatively well observed coastal waters of North America, there is still a significant challenge for interpreting and upscaling relatively sparse measurements to a regional or continental scale (Fennel et al., 2019).

In response, regional-to-global scale *in situ* oceanic observing networks have been developed and deployed, revolutionizing the way that ocean biogeochemistry and biology are studied and providing a new level of understanding of complex global systems. Examples of such networks abound, including the Global Ocean Observing System (GOOS),[1] the U.S. Integrated Ocean Observing System (or IOOS),[2] the Ocean Observatories Initiative (OOI),[3] the African Blue Belt Initiative (BBI),[4] the Australian Integrated Marine Observing System (IMOS),[5] the Biogeochemical-Argo (BGC-Argo) program,[6] the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM), and the EXPort Processes in the Ocean from Remote Sensing (EXPORTS)[7]. However, cost tradeoffs generally dictate that these networks each are designed to answer a limited set of questions, e.g., long-term vs. short-term variability, spatial or temporal coverage, etc. One common strategy for addressing the physical limitations for achieving high spatial coverage with ocean observatories and the need to understand significant variability of the oceans is to prioritize either (a) a limited number of specific, project-targeted sites for high temporal resolution studies (high temporal coverage with low spatial coverage) or (b) greater spatial coverage that limits shorter temporal resolution. For example, OOI and OceanSITES[8] aim to characterize long-term changes (e.g., ocean temperature warming, ocean acidification and deoxygenation) and key processes (e.g., exchanges and interactions at the boundaries between interfaces of the ocean) at unique or representative locations, while the Biogeochemical-Argo program aims to measure key biogeochemical parameters – for which robust sensor technologies already exist – across the entire globe, but at a lower temporal resolution.

This review postulates that achieving data collection at the spatial and temporal scales demanded by the big scientific questions currently being pursued in ocean sciences requires a paradigm shift in the way we approach ocean observing. The development of advanced *in situ* biogeochemical and biological technologies has been a research priority in the oceanographic community for the past decade (e.g., Johnson K.S. et al., 2009; Moore et al., 2009; Byrne et al., 2010; Feely et al., 2010; Moustahfid et al., 2012; Martz et al., 2015). We assert that ocean science and engineering now must focus on dramatically lowering the cost of *in situ* sensors in order to increase spatiotemporal coverage relevant to high-heterogeneity of many biogeochemical and biological processes. To some extent, the evolution of sensors and deployments becoming cost-effective is already underway, often accelerated by the reduction in cost and size of the actual sensor components (e.g., Mills and Fones, 2012). Low cost electronics and computing solutions, hobby-grade electronics, and fabrication technologies (e.g., 3D printers) are being rapidly developed and advanced for other fields and applications outside of ocean science and are being applied to ocean sensor development. For example, though mostly still at the research stage, while a traditional CTD instrument costs ∼\$10k, a new MEMS-based CTD sensor has ∼10-fold lower cost (<\$1k). Similarly, a typical oxygen optode may cost upward of \$10k, repackaging it using low-cost materials and electronics can decrease cost by 5- to 10-fold. As a field we need to learn from such an initiative to transfer cost savings to other variables of interest in ocean biogeochemistry and biology.

This review, therefore, aims to: (1) provide a review of existing sensor technologies that have already demonstrated a decrease in cost compared to previous sensors and methodologies (section "Existing Cost-Effective Sensing Technologies for Biogeochemical EOVs and Relevant Parameters"), (2) present case studies of cost-effective *in situ* deployments that can provide insight into methods for bridging observational gaps (section "Cost-Effective Deployments"), (3) identify key challenge areas where progress in cost reduction is lagging (section "Challenging Areas: Technologies Where Innovation Is Needed for Cost Reduction"), and (4) present a number of potentially transformative directions for future ocean biogeochemical and biological studies using cost-effective technologies and deployment strategies (section "Common Themes and Transformative Future Directions"). In this review we include

[1]http://www.goosocean.org
[2]https://ioos.noaa.gov
[3]https://www.oceanobservatories.org
[4]http://www.laceinturebleue.org
[5]http://www.imos.org.au/
[6]http://www.biogeochemical-argo.org
[7]http://oceanexports.org
[8]http://www.oceansites.org

cost-effective sensing technologies for ocean biogeochemistry and biology to provide an interdisciplinary perspective on available cost-effective *in situ* sensing technologies so the ocean science community can plan and design integrated observing networks using these technologies and because innovations in hardware are likely to be transferable across disciplinary lines.

For the purposes of this analysis we define "low-cost" or "cost-effective" as achieving a decrease in cost of at least threefold or more relative to the cost of established technologies or deployment methods. In other words, we target innovation that theoretically could enable an increase of spatiotemporal resolution by threefold or more, assuming that the lower cost sensor still meets the standards (e.g., accuracy, range, drift) required by specific scientific application. While there is also a need to understand cost in an absolute sense, this relative definition of "cost-effectiveness" provides a lens that is relevant across a wide range of technologies and disciplines. Some biogeochemical sensors may already be "low-cost" (<$1k) while biological sensors are not yet comparable in terms of absolute cost. Although some newly developed biological sensors can be considered to be cost-effective in this context in terms of "cost per data point generated," it becomes clear through this review that affordability of biological *in situ* sensors faces more challenges and needs more improvement from developers and the community to catch up. Furthermore, it must be noted that many *in situ* biogeochemical and biological sensors are first generation sensors, so providing a cost comparison to previous sensors may not possible in all cases.

A complete discussion of all existing cost-effective technologies is beyond the scope of a single review, thus, we aim to present representative sensor technologies that cover important development aspects with respect to cost reduction approaches, including miniaturization, novel sensing modalities, system integration, and unique deployment strategies. By targeting technologies to highlight, we are able to focus primarily on the observational needs and gaps in ocean biogeochemistry and biology, guided by consensus lists of essential ocean variables (EOVs)[9] (**Table 1**). Issues that are universal to all sensors, such as packaging, deployment platforms, power supplies, and communication, are discussed in section "Common Themes and Transformative Future Directions."

[9]http://www.goosocean.org/eov

TABLE 1 | List of essential ocean variables (EOVs) and relevant variables identified by the Global Ocean Observing System (GOOS) Expert Panels, based on criteria taking into account relevance, feasibility, and cost effectiveness (adapted from http://www.goosocean.org).

Biogeochemistry	Biology and ecosystems
Oxygen*	Phytoplankton biomass and diversity*
Nutrients*	Zooplankton biomass and diversity*
Inorganic carbon*	Fish abundance and distribution*
Transient tracers	Marine turtles, birds, mammals abundance and distribution*
Particulate matter*	Hard coral cover and composition
Nitrous oxide	Seagrass cover and composition
Stable carbon isotopes	Macroalgal canopy cover and composition
Dissolved organic carbon	Mangrove cover and composition
Ocean color	Ocean Sound*

**Parameters included in this review.*

EXISTING COST-EFFECTIVE SENSING TECHNOLOGIES FOR BIOGEOCHEMICAL EOVS AND RELEVANT PARAMETERS

In this section, we review a sample of available sensor technologies capable of achieving cost-effective measurement of biogeochemical and biological EOVs or related parameters; a summary of included technologies and estimated technology readiness level (TRL) is provided as **Table 2** for comparison. Technologies are presented roughly in order of degree of readiness, from those which are already commercialized or in wide use to those which are in the research and development stage.

Dissolved Oxygen

Dissolved oxygen (DO) is a key biogeochemical parameter measured for many oceanographic studies. The required DO measurement uncertainty to detect meaningful changes in the open ocean is about 1–2 μmol kg^{-1} (Gruber et al., 2010; Keeling et al., 2010). DO sensors are one of the most mature biogeochemical sensors as a result of advances in detection technology over the last few decades (Bittig et al., 2018). Two commonly used methods for *in situ* DO sensing are the Clark-type electrochemical detection (DO electrode) (Kanwisher, 1959) and luminescence quenching by oxygen (Kautsky, 1939; Körtzinger et al., 2004, 2005; Lakowicz, 2006; Tengberg et al., 2006). The former is simple to instrumentation, but is generally considered to be less accurate and prone to drift during long-term deployments; the latter is more accurate and has led to the development of the oxygen optode, the technology of which has been widely used on almost all observing platforms for more than a decade (Riser et al., 2016). Furthermore, micro-sensors for *in situ* DO detection have been available for many years (Sosna et al., 2007; Chipman et al., 2012).

Cost-effective Clark-type DO sensors are already available for seawater measurements. One approach is to use a bare disk electrode design (Sosna et al., 2007) which – with appropriate *in situ* cleaning – can achieve adequate performance for profiling applications (Sosna et al., 2008). The simplicity of this sensor has also been combined with micro-fabrication techniques and existing lithographic micro-manufactured conductivity (C) and temperature (T) sensors (Huang et al., 2011) to create a combined CT-dissolved oxygen (CT-DO) micro-sensor (Morgan et al., 2014a,b,c,d). The CT-DO device is cost-effective and can be used with pressure balanced, soft or hard potted electronics, obviating the need for pressure cases. This DO sensor has a response time of ~2 s and current accuracy of ~5 μmol kg^{-1} though additional improvements are foreseen. Another example is the Oxyguard DO profiling sensor,[10] which has a fast response time (~10 s) and

[10]http://www.oxyguard.dk

TABLE 2 | Characteristics of cost-effective *in situ* sensing technologies for biogeochemical and biological parameters.

Parameters	Cost-effective sensing technology	Traditional cost level	Cost-effective level	TRL for cost-effective sensors[1]	Availability for cost-effective sensors[2]
DO	Luminescence quenching (optode)	$$$	$	5	Individual researchers
	Clark-type electrode	$$	$	9	Individual researchers; commercial
pH	Spectrophotometric	$$$	$	7	Individual researchers; commercial
	Spectrophotometric	N/A[3]	$$ (Lab-on-a-chip)	7	Individual researchers; pre-commercial
Nitrate					
	Electrochemical	$$$	$	6	Individual researchers; commercial
	Fluorescence	$$$	$$ (Lab-on-a-chip)	5	Individual researchers
Ammonia/Ammonium	Lab-on-a-chip (colorimetric)	N/A	$$	6	Individual researchers; pre-commercial
	Reagentless/electrochemical	N/A	$$	5	Individual researchers
Phosphorous	Lab-on-a-chip (colorimetric)	N/A	$$	7	Individual researchers; pre-commercial
	Reagentless/electrochemical	N/A	$$	6	Individual researchers; pre-commercial
Particle and POC	OBS	$$	$	8	Commercial
	ABS	$$	$	8	Commercial
Phytoplankton biomass	Fluorometric	$$$	$$	9	Commercial
Plankton[4]	Optic (microplankton size fraction >10 μm)	$$$$$	$$$	4	Individual researchers
	Optic (mesoplankton size fraction >100 μm)	$$$$$	$$	7	Individual researchers Commercial
Zooplankton and fish abundance and distribution	Acoustic	$$$$$	$$$$	9	Commercial
Microbes, phytoplankton and zooplankton	Genetic	$$$$$	$$$$	5–6	Individual researchers Commercial

$–$$$$$ signs: relative sensor cost level. [1]Technology readiness level (TRL). These are estimated TRLs based on literature review. [2]See text for more details. [3]Not applicable. [4]Phytoplankton and zooplankton biomass and functional diversity.

is insensitive to hydrogen sulfide interference. Its measurement uncertainty is 1–2%, allowing it to be useful in dynamic systems, such as coastal sites, where a large variability of DO occurs over different time-scales.

Oxygen optode technology has also matured over the last decade, resulting in robust and sensitive sensors capable of collecting climatology-quality data (Bittig et al., 2018) at moderate a investment (∼$3k per unit). However, further reducing the cost of DO optodes is an active research area. For example, an NSF-funded *in situ* mini-DO optode sensor has been under development for the last several years, designed for deployment on small marine organisms, such as jellyfish and squid, to 300 m (**Figure 1**). The sensing element is already commercially available (PreSens, Germany). The use of low-cost components (e.g., synthetic foams and silicone-based epoxy) and improved engineering design allows the cost and power consumption of this mini-O_2 optode to be low (∼$1k, ∼0.2 W). The sensor has a nominal overall uncertainty of ∼±0.5% O_2, a detection limit of 0.1%, and a response time of about 1 min. *In situ* testing of the sensor is currently underway along with efforts to improve the sensor's deployment duration and depth. Currently, such a mini-DO optode may be suitable for short-term deployment (days – weeks) on various platforms, such as free-swimming animals, stationary platforms (e.g., buoys), and vehicles (i.e., Autonomous Underwater Vehicles – AUVs).

These examples of cost-effective *in situ* DO sensors share two key features: the use of low-cost components and new packaging approaches for submersible deployments. It is expected that the main components and materials of DO sensors will continue to decrease, and such sensors may be among the first biogeochemical parameters that can achieve massively cost-effective deployments with a large number of sensors.

The Carbon Dioxide System

The carbon dioxide (CO_2) system is described by four measurable primary parameters: total dissolved inorganic carbon (DIC), partial pressure of CO_2 (pCO_2) or CO_2 fugacity (fCO_2), pH, and total alkalinity (TA), each of which has its own unique applications in marine biogeochemistry. Measurements of any two of the four parameters are required to fully resolve the carbonate system using seawater acid–base equilibria, including calculation of $CaCO_3$ saturation states that are highly relevant

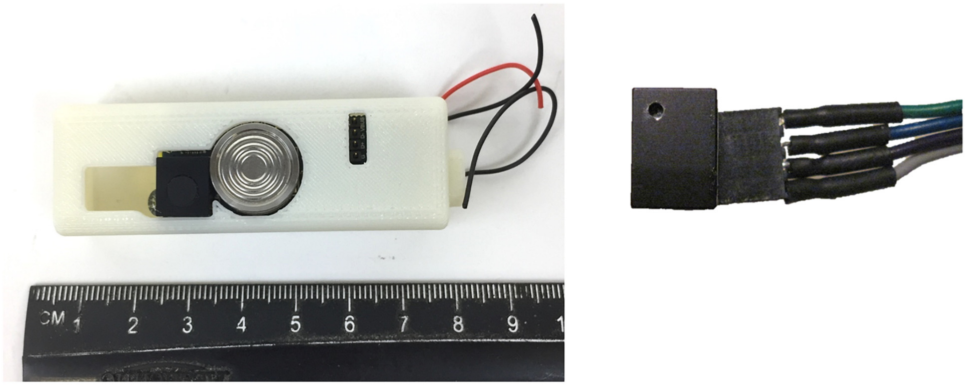

FIGURE 1 | Left: Miniature dissolved oxygen optode assembly (left) in a bio-logging tag platform. The ruler scale is in centimeters. **Right:** O_2 sensing cube (PreSens, Germany) (courtesy by Dr. Z. A. Wang, WHOI, United States).

to OA studies. With continuous efforts invested in developing sensors and instruments for CO_2 parameters in recent decades, significant advancements have been made in this field (Byrne, 2014; Martz et al., 2015). The recent Wendy Schmidt Ocean Health XPRIZE[11] has acted as a global catalyst for developing new pH sensor technologies to improve *in situ* seawater pH measurements. Currently, pCO_2 and pH *in situ* sensing technologies are relatively more mature, with commercial pCO_2 and pH sensors available for seawater applications, though the need to achieve faster-response and deeper deployment is acknowledged.

Two types of *in situ* pH sensors are most widely deployed to measure seawater pH: spectrophotometric (Liu et al., 2006; Gray et al., 2011) and ISFET based pH sensors (Martz et al., 2010; Bresnahan et al., 2014; Takeshita et al., 2014). The electrochemistry-based *in situ* pH electrode is generally considered to be less stable and precise than the other two for seawater applications. SAMI pH (Sunburst Sensors, LLC, United States) and SeaFET (Sea-Bird Scientific, Inc., United States) sensors are, respectively, representative of spectrophotometric and ISFET based *in situ* pH sensors, which can achieve high-quality measurements if properly calibrated and deployed. However, these commercial sensors still cost more than $10k per unit.

In recent years, there has been progress in the development of low-cost pH sensors to improve marine carbon and OA research. A low-cost (∼75% cost decrease) commercial spectrophotometric pH sensor, iSAMI, is being developed for surface measurements with good measurement quality[12] (**Figure 2**). In addition, Sunburst Sensors has developed a commercially available handheld pH sensor, pHyter (**Figure 3**) (<$0.5k). Meanwhile, the pH photometer developed by the University of South Florida (**Figure 4**) has a "Do-it-yourself" (DIY) design, is low-maintenance, and achieves good quality measurements (±0.01). This sensor is an order of magnitude cheaper than commercial pH sensors that use similar operational principles (Yang et al., 2014, <$0.3k in material and fabrication). Such handheld sensors are particularly attractive tools for engaging citizen scientists and students in OA monitoring, education and research, and the technology has the potential to be further developed for *in situ* platforms.

In situ pCO_2 sensors in general use either CO_2 equilibration between the sample seawater and a medium (air/gas or reagent such as a pH sensitive dye), followed by infrared or colorimetric spectroscopy of the CO_2-equilibrated medium (e.g., CONTROS HydroC CO_2, Norway; Pro-Oceanus CO_2, Canada; SAMI-pCO_2, Sunburst Sensors, United States). However, these are not typically cost-effective. Miniaturization and cost reduction of these techniques are therefore areas of active research. Over the last decade, the cost of non-dispersive infrared (NDIR) detectors used in pCO_2 sensors has decreased (e.g., a low cost NDIR CO_2 detector is on the order of $100), paving the way for lower cost *in situ* pCO_2 sensors.

Alternately, a number of groups are now developing pCO_2 optodes (Atamanchuk et al., 2014; Clarke et al., 2017; Staudinger et al., 2018). The method is based on CO_2 equilibration between seawater and a pH sensitive fluorescent dye, followed by fluorescent detection, such as the frequency domain-Dual Lifetime Referencing (f-DLR) method (Atamanchuk et al., 2014) or the time domain-Dual Lifetime Referencing (t-DLR) method (Clarke et al., 2015). The fluorescent dye is reusable, eliminating the need for pumping and replacing reagents, which can reduce the complexity for *in situ* sensors. These systems in principle operate similarly as DO optodes, thus having the potential to be low cost as DO optodes. However, long-term stability and measurement quality at marine pCO_2 levels remains an area of active assessment.

While measurement of any two of the four parameters allows full resolution of the carbonate system using seawater acid–base equilibria, large calculation errors result when pCO_2 and pH are used due to their strong co-variation (Millero, 2007). The errors are often minimized when the DIC-pH or DIC-pCO_2 pair is used (Byrne et al., 2010). Even when TA contains a significant amount of undefined alkalinity (e.g., organic alkalinity), the DIC-pH or DIC-pCO_2 pair can still

[11]http://oceanhealth.xprize.org

[12]http://sunburstsensors.com/products/isami-ph.html

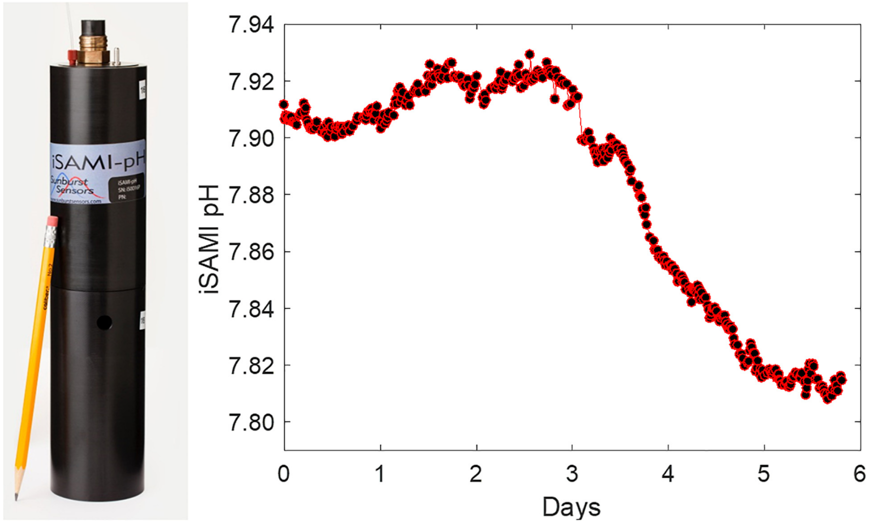

FIGURE 2 | Left: iSAMI pH sensor by Sunburst Sensors, LLC. **Right:** The *in situ* testing of iSAMI pH over 6 days (courtesy by Dr. M. DeGrandpre, University of Montana, United States).

FIGURE 3 | Sunburst pHyter, a hand-held pH meter, with controlling mobile app (courtesy by Dr. M. DeGrandpre, University of Montana, United States).

accurately calculate carbonate alkalinity and $CaCO_3$ saturation states. Therefore, development of *in situ* DIC or TA sensors is of high interest.

In situ sensor technologies for DIC are much less mature (Byrne, 2014; Martz et al., 2015), and currently no commercial *in situ* DIC sensors are available. Various "research type" *in situ* sensors and underway instruments for DIC measurements have been emerging in recent years (Sayles and Eck, 2009; Liu et al., 2013; Wang et al., 2013a,b; Fassbender et al., 2015). These proto-type systems have already achieved significant cost-reductions relative to discrete measurements of bottle samples by several folds. *In situ* DIC detection is based on CO_2 equilibration between an acidified sample and a standard solution through a gas permeable membrane, followed by either spectrophotometric, conductometric, or infrared detection. As lower cost components are developed for other applications, we would expect the costs of these sensors to decrease. For example, built on the technology developed for the Channelized Optical System (CHANOS; Wang et al., 2015), a new miniaturized, lower cost version (CHANOS II) is under field testing, aiming for deployment on profilers, AUVs and remotely operated vehicles (ROVs) with high measurement frequency (1 Hz). In addition, it is designed to make simultaneous measurements of the DIC-pH pair or the DIC-pCO$_2$ pair based on spectrophotometric principles, thus fully resolving the seawater CO_2 system with less calculation errors in many cases. The target price for the CHANOS II shallow-water version (<500 m) is <\$15k per unit with two CO_2 parameters.

Prototype *in situ* alkalinity sensors, such as spectrophotometric SAMI-Alk (Sunburst Sensors, LLC) (Spaulding et al., 2014) and ISFET-based solid state alkalinity sensors (Briggs et al., 2017), are also emerging, and have the potential to achieve low cost, similar to other pH, pCO$_2$, and DIC sensors due to the similarity of detection principles (i.e., spectrophotometric and ISFET). These new TA and DIC sensors have all been developed with the goal of climate-quality

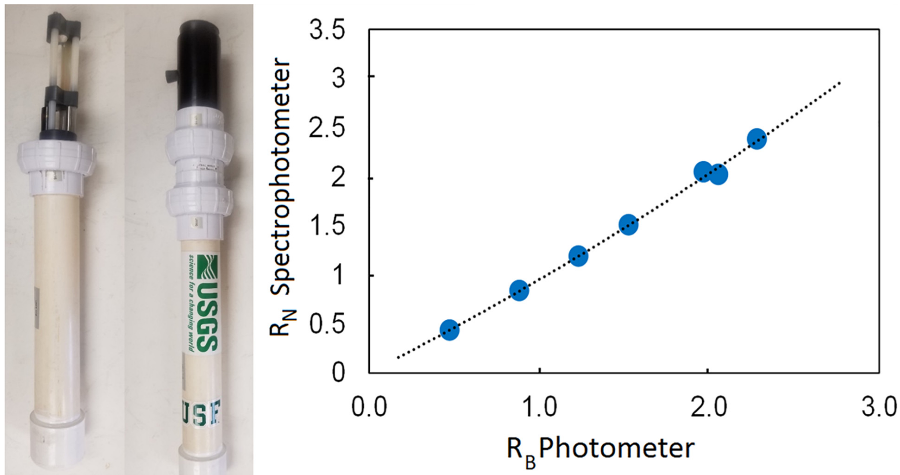

FIGURE 4 | Left: A USF-USGS hand-held pH photometer. **Right:** Photometer (Unit 115) calibration curve of absorbance ratio R_B against spectrophotometrically determined absorbance ratio R_N (courtesy by Dr. R. H. Byrne, University of South Florida, United States). Absorbance ratio R_B is a function of water pH. The dotted line represents the polynomial best fit, $Y = 00679x^2 + 0.8783x + 0.0021$; $R^2 = 0.9971$.

measurements as defined by the Global Ocean Acidification Observing Network[13].

While originally applied for nutrient sensing, Lab-on-a-chip (LOC) technology has also been applied to the *in situ* detection of pH (Rerolle et al., 2018), DIC, and TA. LOC sensors have been developed with a target of being cost-effective, yet high performance *in situ* sensors suitable for mass deployment on various ocean observing platforms. In the LOC platform designed at the National Oceanography Centre, UK (NOC), the principal engineering choices that enable lower costs are the use of a pressure balanced design which obviates expensive pressure cases, optical windows, and electrical connections. Pressure is equalized inside a low-cost polymer electronics housing using an insulating oil. The sensors use microfluidic technologies to mix the seawater sample with pH indicators to produce a color (for pH and TA) or conductivity (for DIC) change to measure the parameter of interest. The TA sensor is based on the single-point spectrophotometric titration method (Breland and Byrne, 1993). The prototype LOC DIC sensor is based on a conductometric method (Sayles and Eck, 2009). Both the LOC TA and DIC sensors take advantage of a development by Li et al. (2013) who used a gas-permeable Teflon AF 2400 membrane (Wang et al., 2002, 2007) to remove the CO_2 from the sample-titrant mixture. The LOC TA and DIC sensors have been deployed on a benthic lander in the North Sea, through a shipboard underway system, and in an estuary. By 2020, the LOC TA and DIC sensors will be integrated into a single device and, together with the LOC pH sensor, will form a package capable of over determining the carbonate system, to allow the measurements to be validated. Cost is currently dominated by the valve, pump, and electronics components. The goal is to reduce the total component costs to \$2.5k in the short term (<1 year) with a target of <\$1k beyond that.

[13]http://goa-on.org/

In summary, the examples described above highlighted several innovations of lowering the costs for CO_2 parameter sensors, including reagentless detection, simultaneous detections of multiple parameters, low-cost materials and packaging, and microfluidic designs. The encouraging trend in recent developments was to embed system designs with both good measurement quality and cost reduction of the systems starting from the early stage of development.

Nutrients

In the context of marine systems, key nutrients of interest are nitrate, nitrite, ammonium, phosphate, silicate, and a number of trace metals (e.g., iron). Nutrients have historically been more difficult to measure *in situ* than physical or bulk chemical parameters, due both to cross-sensitivities with other constituents and to challenges with miniaturization of lab instrumentation for field deployment. While there are a number of commercially available multi-parameter instruments for nutrient measurements in the marine environment (comprehensive list in the ACT Technologies Database[14]), many of these are now mature technologies that are still relatively costly, unlikely to see further decreases in cost and likely to see only incremental improvements in accuracy. A number of emerging technologies, however, build on insights gained from these instruments and may have the potential to meet decreased size, cost, and/or power demands.

The most common strategy for *in situ* nutrient measurement is through the use of wet chemical sensors based on standard laboratory and shipboard principles (spectrophotometry or fluorescence), which can achieve detection limits in the micromolar range for most analytes but require reagents (necessitating volume increases and constraining deployment times) and are still moderately large and expensive (>\$10k).

[14]http://www.act-us.info/database.php

The logical pathway forward is to take advantage of the specificity and accuracy of spectroscopic methods and miniaturize using methods such as LOC which have lower reagent consumption, power consumption, and cost (3–10× decrease). LOC approaches have already been developed and proven in the lab for colorimetric measurements of nitrate [detection limit of 0.025 μmol kg^{-1} (Beaton et al., 2012)] (**Figure 5**), phosphate [detection limit of 40 nM (Clinton-Bailey et al., 2017)], and silicate [in coastal waters (Cao et al., 2017)]. These sensors have very low power consumption [e.g., 1.8 W for one measurement per 15 min (Clinton-Bailey et al., 2017)], and with LOC systems multiple detection cells can be integrated with little increase of cost. Versions for the measurement of ammonium and iron (Geißler et al., 2017) are in development. Related efforts (e.g., a reflectance sensor using optical fibers and miniaturized flow systems) exist for the measurement of dissolved iron using chelating disks and reagents that complex capture iron (Pons et al., 2005).

Reagentless sensors (e.g., based on direct optical UV absorption measurement) have already been commercialized for the measurement of nitrate in waters with relatively low turbidity and colored dissolved organic carbon (DOC) (Finch et al., 1998; Johnson and Coletti, 2002; Zielinski et al., 2007; Sakamoto et al., 2017; Meyer et al., 2018). While these sensors are at a low enough cost that they are now standard on some profiling floats [e.g., the BGC-Argo and SOCCOM programs (Johnson et al., 2017)], the absolute cost per sensor remains high (order of $10k) and therefore alternate approaches (e.g., reagentless electrochemistry) are also emerging. An indium tin oxide (ITO) sensor was demonstrated in 2017 for detecting ammonia in seawater (Lee et al., 2017) while reagentless measurement of silicate and phosphate *in situ* has recently been validated for seawater use (Barus et al., 2018). This latter instrument utilizes a two-cell configuration (complexation with molybdenum, detection using gold working and silver reference electrodes) and achieves a micromolar detection limit, has a sampling period of approximately 1 h, is small in size (100 mm diameter, 186 mm height packaged), and has a low power consumption (25 mAh for 1 sample per hour). Finally, while interferences due to the high salt content of marine waters remain high, the consideration of using potentiometric sensors (i.e., ion selective electrodes) for nutrient measurement in marine environments is ongoing, with several already commercially available (e.g., NISE by Hach Lange, EXO by YSI). Successes in pressure compensating semiconductor (ISFET) pH electrodes (Johnson et al., 2016) and progress in membrane specificity [e.g., for Cl^{-} (Takeshita et al., 2014)] will continue to propel this type of technology forward. Costs for typical ISEs (individual probes, before instrument integration) is on the order of $0.2–$0.9k.

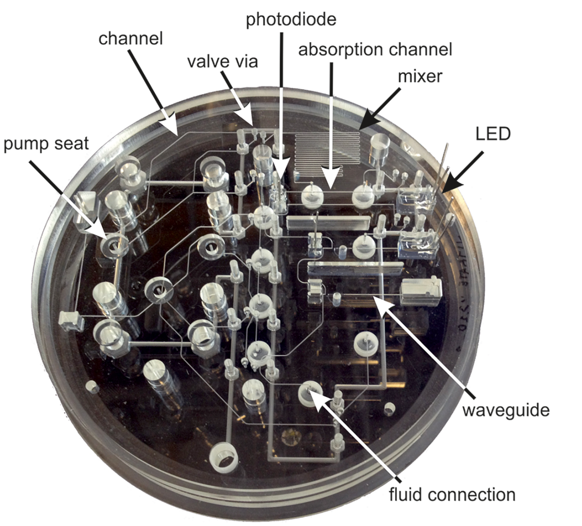

FIGURE 5 | Labeled photograph of a LOC nitrate sensor microfluidic and optofluidic manifold (aka the chip). This 12 cm diameter chip is shown in clear Polymethylmethacrylate (PMMA) to aid visualization. Operational devices are made in tinted PMMA to suppress stray, scattered and ambient light (Ogilvie et al., 2010; Floquet et al., 2011).

Innovation in both classes of sensors show similar strategies for decreasing costs and improving deployability, particularly miniaturization, which frequently comes with decreasing power consumption. Reagentless sensing strategies, however, rely on continued innovation in material science, including identifying membranes, chelators, and electrodes that have fewer interferences or multi-step processes that can separate target nutrients from potentially interfering signals.

Suspended Particles and Particulate Organic Carbon

Instruments employing backscattering techniques (acoustic and optical backscatter sensors, ABS and OBS) provide a means of sampling suspended particle concentration at a relatively low cost (on the order of $1.3–5k per unit) with a small overall package size. Both ABS and OBS technology may be characterized as mature. The measurement techniques and the cost per unit of the commercial sensors have been essentially static over the last two decades, partially because of their already low cost compared to other oceanic sensors. Because of their wide range of application and low cost, they are relevant for this review, especially when integrating with other sensors to provide more cost-effective deployments.

As ABS instruments do not rely on an optical signal, they are less prone to degradation due to biofouling of the sensor head than an OBS. However, a number of manufacturers offer an OBS with an optical sensor wiper or shutter to cover the sensor head when not taking measurements (e.g., Seabird Sci. ECO Scattering sensor and Campbell Scientific OBS501). A principal distinction between ABS and OBS devices is the range of particle sizes to which they are sensitive. An OBS is most sensitive to fine-grain particles to roughly 40 μm grain size, with the backscatter signal dominated by particles in the 1–10 μm size range (Organelli et al., 2018). By contrast, an ABS is most sensitive to coarser particles, in the 30–400 μm grain-size range. This distinction has prompted some investigators to pair an OBS and ABS to maximize the overall grain size range measured (Hawley, 2004). Seapoint Sensors Inc. has recently developed technology that extends the OBS measurement range to much higher concentrations (well in excess of twice the maximum concentration sensed by the company's earlier OBS models). The OBS employing this technology (the STM-S) is offered at roughly the same price (~$1.3k) as the company's earlier models, equivalent to a cost-reduction with updated capability.

The signal of an OBS can be used to determine the concentration of particulate organic carbon (POC) using a derived POC-concentration vs. OBS-intensity relationship for a given marine area (Briggs et al., 2011; Cetinìc et al., 2012; Johnson et al., 2017). This makes an OBS valuable for studying oceanic biogeochemistry, particularly when the OBS is combined with sensors that measure other relevant properties, such as chlorophyll-*a* and colored dissolved organic matter (CDOM). Instrument packages combining an OBS with CDOM and chlorophyll-a fluorometers are commercially available (at unit cost of order $13k) in sizes suitable for use on moorings and/or mobile platforms (e.g., Seabird Sci. ECO Triplet; Alkire et al., 2014; Roesler et al., 2017).

For observations directed at sediment dynamics in the bottom boundary layer, a profiling ABS offers a useful means of monitoring SPM concentrations at selected distances above the bottom. A number of studies have shown that profiles of SPM concentrations may be obtained with high accuracy using the returns from multi-frequency ABS as well as from a conventional acoustic Doppler current profiler (ADCP) provided that the acoustic return signals are calibrated with coincident measurements of SPM concentration using the sediment characteristic of the measurement site (e.g., Thorne and Hardcastle, 1997; Gartner, 2004; Sahin et al., 2017). Profiling ABS systems employing transducers with a range of frequencies (to provide sensitivity over a range of particle sizes) and suitable for long-term deployment are available at a cost of ~$15k (e.g., AquaScan 1000 by Aquatec Group Ltd.).

Overall, the commercial sensors in this category are relatively robust. Improvement of cost-effectiveness of their use in comprehensive oceanographic studies, targeting a host of variables, may be expected in the near future, given the trend of sensor integration (i.e., combining particle sensors with sensors for other variables) currently underway. Furthermore, advances in relating the instrument signal to SPC may be expected in the near future. As recently demonstrated by Organelli et al. (2018), the backscattering signal to SPC relationship is sensitive to the structural complexity of the particles measured, revealing the need for further research to optimize *in situ* detection of marine particles using backscattering techniques. Further cost-reduction of these sensors may be needed to enable large-scale deployment described in this paper.

Fluorescence and Chlorophyll

Quantifying phytoplankton biomass *in situ* using *in vivo* chlorophyll fluorescence has been widely employed for more than half a century. It becomes a routine observation because it is fast and adaptable to various deployment platforms (Boss et al., 2018; Lombard et al., 2019). The method is based on the assumption that the fluorescence intensity of chlorophyll-*a* and its concentration are directly proportional to one another. However, chlorophyll fluorescence measurements in the applicable spectrum range (680–685 nm) have many sources of uncertainty, arising from device hardware (e.g., excitation light and detector) as well as interferences or variability in aquatic environments, such as changes in phytoplankton physiology, photo-acclimation, growth phase, non-photochemical quenching, nutrient limitation, and high CDOM concentration interference (Kiefer, 1973; Cullen, 1982; Xing et al., 2017). To date, the most robust and rigorous procedure to correct the raw data is to compare high pressure liquid chromatography (HPLC) measurements of discrete water samples with sensor observations (Lombard et al., 2019). Existing data must go through vigorous quality checks before use (Boss et al., 2018). For example, Roesler et al. (2017) recommended that the chlorophyll-a values obtained with WET Labs ECO FLBB sensors in the past be corrected by a factor of two in order to produce a global set of data with a relatively small bias compared to global average HPLC measured values.

Because of recent technological advances, miniaturized and/or cost-effective *in situ* fluorometers are emerging. Leeuw et al. (2013) developed a fluorometer (about $0.15k) which can be deployed in large quantities (e.g., in an array) to detect and monitor the development of phytoplankton blooms over a large spatial scale, such as harmful algal blooms. Blockstein and Yadid-Pecht (2014) also reported proof-of-concept miniature fluorometers (<$0.5k) which can measure chlorophyll and CDOM simultaneously. Another innovation is the T-FLaP technology (Marcelli et al., 2014), which is capable of obtaining vertical profiles of fluorescence of chlorophyll-*a* or to be used as a stand-alone system for surface mapping. Friedrichs et al. (2017) presented a prototype DIY device, SmartFluo, which consists of a smartphone operation interface, a cuvette adapter, and an illumination source. It is designed for applications in inland and coastal waters, and is useful for citizen science.

In general, these innovations and massive cost decreases have been achieved by capitalizing on mass-produced electronics and miniaturization. Although these new technologies still require regular calibration, and may require additional improvement on detection limit and accuracy before they can be used at scale for oceanographic research, they are a promising proof-of-concept step in the direction of massively increased sensing resolution.

Underwater Bio-Acoustics

Passive and active acoustic sensing are capable of delivering datasets of relevance to several EOVs, including fish abundance and distribution (Simmonds and MacLennan, 2005), marine mammal distributions (Brehmer et al., 2012), diving seabird behaviors (Benoit-Bird et al., 2011; Williamson et al., 2017), habitat type and fine-scale topography (Roberts et al., 2005; Smith and McConnaughey, 2016) and ocean sound (Hildebrand, 2009). Although the absolute price tag may not be comparable with available low-cost biogeochemical sensors, the multi-purposes and high data output per unit cost of bio-acoustic sensors allow them become a cost-effective way of studying a wide range of biological processes and marine organisms, along with their living habitats in the last decade. Technology development and material advancement in recent years also helped to reduce the costs of acoustic systems, allowing more accessibility for ocean research. Here, we focus on active acoustic technologies that have achieved major advances in the last decade for marine biological purposes. Today, fisheries acoustics (Simmonds and MacLennan, 2005) is a central discipline for *in situ* observations of aquatic organisms extending from plankton to whales (Brehmer, 2006). Acoustics transducer accuracy and reliability are paramount when making biological measurements with acoustic transducers. There exists a wide range of transducers that deliver results of interest for marine scientists, fisheries, and conservation managers, including echosounder and sonar systems. During the last few decades, the main advance is the advent of multibeam (e.g., Guillard et al., 2011) and wideband (Demer et al., 2017; Jech et al., 2017) acoustic systems, although calibration and data treatment are still challenging with existing protocols (e.g., Perrot et al., 2014, 2018; Demer et al., 2015; Korneliussen et al., 2016; Eleftherakis et al., 2018).

Rapid advances in the miniaturization of acoustic sensors (transducers) and the improvement of batteries and computers allow them to be mounted on various mobile platforms, such as gliders and AUVs (Hine et al., 2009; Moline et al., 2015) and buoys (Godo and Totland, 1999; Brehmer et al., 2018), thus rendering this sensing technology cost-effective both in hardware and in deployment compared to traditional shipboard transducers. In the last decade, a new cost-effective multi-purpose scientific echosounder, the Simrad EK15, was designed and validated (Betanzos et al., 2016; Linløkken et al., 2019). Another major development in cost-effective acoustic sensing is the scientific wide band echosounders (Demer et al., 2017) which use a wide band transceiver (WBT) to replace the general purpose transceiver (GPT) that is used for narrow-bandwidth echosounders, e.g., the WBT Miniature wideband transceiver (WBT Mini) (Benoit-Bird et al., 2018), wide-band autonomous transceiver (WBAT), and WBT Tube Subsea transceiver (WBT Tube) (Lavery et al., 2017). Such systems are compact in size and energy efficient, making them useful as a portable echosounder or for installation on a wide range of platforms (e.g., Saildrone by Mordy et al., 2017). This allows long-term deployments in challenging environments (Demer et al., 2017), such as in the arctic, using the Acoustic Zooplankton and Fish Profiler (Ludvigsen et al., 2018).

Multibeam systems such as long-range omnidirectional sonar (Brehmer et al., 2006), multibeam sonar (Korneliussen et al., 2009), and multibeam echosounder (Trenkel et al., 2008) have become more reliable and cost-efficient per unit of data output (e.g., Trygonis et al., 2016; Dunlop et al., 2018). Acoustic cameras have been emerging for fine scale studies of marine organisms in the last decade (Tušer et al., 2014; Martignac et al., 2015), which have provided new detailed knowledge on their living behaviors and physiology. The next step in lowering the overall cost in this field is to capture habitat characteristics at the fine scale (Bertrand et al., 2014) simultaneously with marine organism detections, and applying data processing and analytics from several acoustic sensors (Brehmer et al., 2002). Future concepts for fine scale studies (>20 m) have been presented by Gerlotto et al. (2011) by building and operating a high-frequency, three-dimensional sonar that will allow observation and analysis of fine scale dynamics within marine organism aggregations. Such an approach requires non-conventional concepts as traditional sonars are limited by physical constraints, making observational improvements difficult. Remaining issues of active acoustics systems include relatively high power consumption for autonomous deployment and delivery of large-size data streams generated in a wide range of modulation frequencies.

For systems discussed here, it is a combination of newly available electronics and improvements in battery technologies that have enabled miniaturization of the technologies and particularly, therefore, deployment aboard more cost-effective deployment platforms.

COST-EFFECTIVE DEPLOYMENTS

Deployment strategies for cost-effective sensing technologies are a key factor for determining the overall cost of any field effort, and thus the long-term sustainability of ocean observing. For example, small boats and ships of opportunity can provide platforms for deployment and access to flow-through water systems. Lower-cost autonomous surface platforms, such as the JetYak (Kimball et al., 2014) with a <\$20k price tag, can become platforms devoted to chemical sensing, as demonstrated by the recent development of the ChemYak (Nicholson et al., 2018) which includes laser-based sensors for dissolved methane and $p\text{CO}_2$ measurements in addition to an oxygen optode and a nitrate sensor. In this section, we describe a few case studies of cost-effective sensor deployments. Although the *in situ* sensors used in these cases may not all be low cost, the platforms and methodologies are presented as valuable examples for achieving cost-effective deployments.

Democratizing Access to Ocean Observing Technology

Working with a network of traditional Hawaiian Fishpond restoration groups, the group of Dr. B. Glazer at the University of Hawaii (UH) is reducing costs of deploying real-time observing networks of sensors for water level, temperature (accuracy ∼0.1°C), and other environmental variables at high spatiotemporal resolution that are sufficient to characterize streams, tides, and episodic flooding[15]. The traditional Hawaiian Fishponds, Loko iʻa, represent a long-lasting example of one of the ancient world's more significant and successful aquaculture achievements (Keala, 2007); as they are comprised of inputs and outputs over manageable and semi-controlled spatial scales (**Figure 6**), these fishponds provide ideal natural laboratories for testing new technologies that can improve spatial and temporal resolution of predictive coastal physical, chemical, and ecosystem models (e.g., Briggs et al., 2013).

For the prototype network deployed at Heʻeia Fishpond, three styles of low-cost *mini-Nodes* have been developed: (1) Arduino-controlled telemetry dongles that parse and relay any serial data from industry-standard instruments such as Seabird SBE19+ (node-025), (2) BeagleBone Black-controlled multi-parameter packages that log data from Aanderaa oxygen optodes,

[15] http://www.smartcoastlines.org

FIGURE 6 | He'eia Fishpond, Oahu, is an 800-year old, 88-acre coastal walled estuary. Sluice gates (mākāhās) allow for tidal exchange with adjacent Kaneohe Bay. Paepae o He'eia (PoH) is a local non-profit organization dedicated to the cultural and environmental restoration of the pond (photo courtesy by Paepae o He'eia).

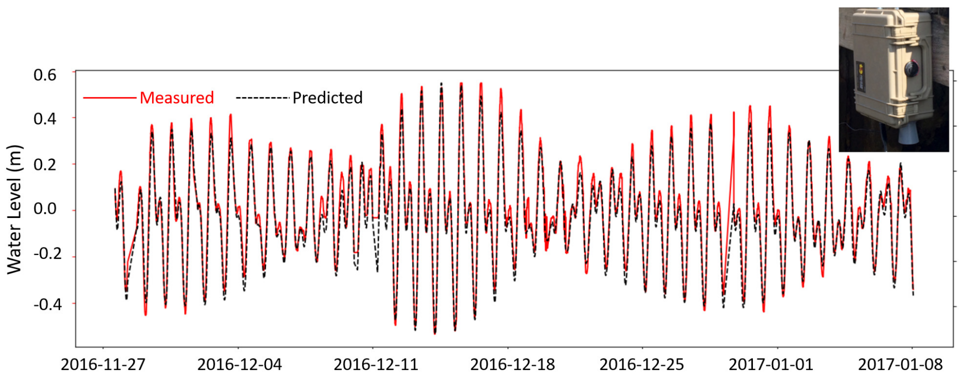

FIGURE 7 | Low-cost temperature compensated ultrasonic sensor mounted above the water level in a He'eia Fishpond mākāhā (upper right inset) provides near-real-time tidal observations (red, solid line) that compare well with nearby US NOAA tide gauge observations (yellow dashed) and show promise for generating site-specific tide predictions using open-source Python software package, uTide (black, dashed line).

Aanderaa conductivity sensors, low-cost MEMS barometric pressure-temperature-humidity sensors, and submersible MEMS piezo-resistive pressure sensors (node-003), and (3) Arduino controlled temperature-compensated ultrasonic sensors mounted on bridges over sluice gates (mâkâhâs) in the Fishpond wall to monitor water level (tidal exchange with Kaneohe Bay). For each configuration, data are telemetered back to a shore-side base station where data are logged into an SQL database, stored, and transferred to a server at UH Mānoa (UHM). At UHM, an x86 Linux server (*NUC5i7RYH*) performs automatic, first-pass QA/QC data filtering and flags data that is out of expected range or *mini-Nodes* that have not reported as scheduled. Data are then served on the web via an open-architecture *RESTful* API (**Figure 7**).

Three specific advances in low-cost electrical components and software tools are making these new deployments possible and timely: (1) the availability of low-cost powerful single-board microcomputers and microcontrollers (e.g., BeagleBone Black, *Texas Instruments*, \$55; ATMEGA32U4, Arduino-compatible, \$5), (2) robust low-power radio frequency (RF) wireless mesh network transceivers (XBee Pro 900HP, *Digi*., \$39), and (3) growing popularity and capability of crowd-sourced open-source software tools (i.e., Linux-operating system, Python embedded systems control and visualization libraries, and GitHub coordinated version control development). What once required a team of computer scientists and engineers to implement can now be prototyped, tested, and deployed with a much smaller team and largely open-source hardware and software tools. Such a deployment is representative of combining user-derived low-cost communication and control, sensing packages, data processing, and engagement of citizen science to establish a socially relevant ocean observing network.

Designing Cost-Effective Deployments With Miniaturized Sensors

Miniaturized low-power sensors can enable long deployments with minimal human intervention, particularly in difficult-to-access environments. As was highlighted in several cases in section "Existing Cost-Effective Sensing Technologies for Biogeochemical EOVs and Relevant Parameters," LOC sensing technology is a new way to miniaturize complex sensing systems and reduce overall device cost. However, their modest size and power consumption also permit cost-effective design of deployments. Low reagent consumption allows for regular recalibration *in situ*, providing high-quality data over long periods. As examples, the trace metal (Milani et al., 2015; Geißler et al., 2017), nitrate/nitrite (Beaton et al., 2012) and phosphate (Clinton-Bailey et al., 2017) versions of the LOC sensors have been deployed at a coastal observatory in an estuary/fluvial setting providing continuous measurements for up to 18 months with reagent replacement only required every 3 months. This has revealed excellent field metrology and matching to standard water sample data (e.g., nitrate detection limit <25 nM), as well as surprising resilience to fouling.

In the cases of the LOC sensors described above, the rugged pressure balanced design permits their use in extreme environments which are expensive to access regularly. For example, the nitrate/nitrite LOC sensors have been deployed in a proglacial melt stream (Beaton et al., 2017), in the Mauritanian oxygen minimum zone, and offshore of Western Africa (Yucel et al., 2015) where high quality data was successfully collected via profiling (up to 60 m depth) and onboard a lander (to 170 m depth). The deepest deployment of this technology to date has been to 4800 m in trials in the region of the Porcupine Abyssal Plain observatory on a CTD frame where data matched bottle samples.

Another route to cost-effective deployments is through the use of multiple miniature sensors on a single platform. As an example, nitrate, phosphate and pH (Rerolle et al., 2018) LOCs were deployed simultaneously on the NERC Autosub Long Range (ALR) and on a lander (Sonardyne, United Kingdom) to develop monitoring systems for offshore carbon capture and storage reservoir integrity verification systems. Herein the systems on the lander were able to detect the stoichiometric signature of a simulated (deliberate gas release) leak. Other recent examples of deployment on low-power autonomous vehicles include use on a profiling float (PROVOR, NKE, France) as part of the EU SenseOCEAN project[16] and onboard a Kongsberg Seaglider in coastal and shelf systems, measuring nitrate/nitrite (Vincent et al., 2018) and phosphate. These deployments show the ability of the sensor and AUV to capture simultaneous, high spatiotemporal variability of physical parameters and nutrients, revealing previously obscured processes and features.

While often cited as a likely problem for LOC, fouling has not been a significant issue that degraded LOC's performance. The so-far longest data set obtained without reagent resupply or intervention was >1 year from a nitrate/nitrite sensor deployed on the FixO3 mooring in the Fram Strait. Although the cold and dark conditions in this annually ice covered region (less biofouling) assisted long-term preservation of reagents, other fouling and challenges in low-temperature environments did not degrade sensors' performance during the deployment period.

Animal Oceanographers

Animal-Borne Sensors (AnBS) have been used for decades to deliver physical oceanographic data and animal behavior observations at a relatively low cost (Roquet et al., 2017). AnBSs are increasingly vital as we seek to observe changing oceans in greater temporal and spatial resolution as they offer a cost-effective strategy for autonomous sampling, with the sensor packages often on the scale of several hundred to a few thousand dollars per tag-package. The ability to affix tags to many animals means there are many tag concurrently making observations. While early AnBSs tended to record relatively basic information such as dive depth, duration, and temperature, innovative use of simple sensors, such as pressure to address ascent or descent rates and particular tracks, provides insight beyond behaviors such as foraging strategies, biological hotspots, occurrence rates (abundances), and relative densities of poorly understood (prey) layers (Johnson M. et al., 2009; Arranz et al., 2011).

AnBSs have typically been applied to large vertebrates that can easily carry the tags. Sharks, tunas, salmon, sturgeon, marine mammals, reptiles, and seabirds have been routinely tagged with sophisticated instruments that sample biological behaviors (diving) and/or oceanographic variables (e.g., pressure, light, temperature, salinity, DO, chlorophyll fluorescence). The horizontal range of measurement is highly variable, depending on the organism outfitted with the AnBS, and can be as small as bays and estuaries but as large as ocean basins when leveraging some large vertebrates. High resolution movement sensors (e.g., gyroscopes, magnetometers, accelerometers) enable observation of the animal's biological activity and physiology within those conditions) (Wilson et al., 2006). These data on habitat and habitat use are particularly relevant for endangered species (e.g., bluefin tunas), protected taxa (cetaceans), and regions of concern (Block et al., 2011; Fedak, 2013; Roquet et al., 2013).

A major challenge to AnBSs is data storage and transmission. Two general modes of data collection exist to address these challenges. First, data storage tags may record observations in higher resolution but the tag has to be recovered to acquire the data. These sensors may "pop-off" the animal and be recovered at sea, or in the case of elephant seals and other pinnipeds, the AnBSs record high resolution data (often temperature, salinity, oxygen, but also echo sounder data) and the sensor tag is recovered when the animal returns to the rookery or shore (e.g., Lawson et al., 2015). Sometimes the sensors also require recovery for recalibration (as in the case of some oxygen sensors), otherwise assumptions of sensor drift and expected conditions have to be applied, limiting some data resolution or applications. The second general data conveyance method is to relay information through a network (Dragon et al., 2010; Blain et al., 2013). This has long been through the aging ARGOS satellite network. These can be relatively small transmitter-tags but the data is limited by the network thus measurements are often lower-resolution. Iridium hardware is still usually too big for most animals to handle. Cell networks are increasingly being used in areas where service is available (near shore). These methods can be combined, relaying low-resolution data through ARGOS and acquiring high resolution data if/when the AnBS is recovered.

With a cost of a few hundred to a few thousand dollars, AnBSs tend to be relatively cost-effective oceanographic sensor packages. New tag developments are striving to miniaturize sensors which would allow expanded use beyond the large vertebrates. These efforts include AnBSs carried by soft-bodied invertebrates such as jellyfish and squid (Mooney et al., 2015; Fossette et al., 2016) (**Figure 8**). Many inertial motion sensors are widely available, thus driving down costs. Leveraging these and other "off-the-shelf" sensors would help in further cost-reduction. 3D housing printing would reduce manufacturing costs. Additionally,

[16]https://cordis.europa.eu/project/rcn/110898/factsheet/en

improving data transfer, perhaps through microsatellites, would help cost-efficiency of gaining the observational data.

CHALLENGING AREAS: TECHNOLOGIES WHERE INNOVATION IS NEEDED FOR COST REDUCTION

In this section, we review recent developments of two areas of active research on biological sensors. Although continuous innovations are required to lower the cost of these sensor systems for large-scale deployment, there have been significant advancement in these areas in terms of both technology and cost reduction. Discussion on a more extensive list of biological *in situ* sensor technologies can be found in the review by Lombard et al. (2019).

Optical Sensors for *in situ* Plankton Monitoring

Optical monitoring of plankton EOVs (phytoplankton and zooplankton abundances and functional diversity) is challenging and often requires high resolution imaging systems together with dedicated data analysis systems (Picheral et al., 2010), driving up costs (into to $100k range). Various systems have been developed for plankton or particles greater than 10–20 μm, replacing the high-cost laser optical plankton counter (LOPC) (Herman et al., 2004). Rapid advances in electro-optical technology have resulted in new and better ways of illuminating, detecting, and imaging plankton *in situ*, which has the potential to lower the costs of the systems. Prototypes or commercially available high resolution imaging systems now allow plankton and particles to be detected across a wide range of sizes, up to the centimeter scale. The hardware part of these systems is now mature and additional miniaturization efforts has allowed these sensors to become fully adaptable on autonomous platforms (e.g., floats and gliders) (Boss et al., 2018; Ohman et al., 2019). These technological progresses can be integrated with existing data protocols to allow cross comparison from quantitative data set (Lombard et al., 2019).

For organisms larger than 100 μm, the number of available sensors has increased drastically over the last decade and several are available at reasonable costs (<$100k) with a high capacity of data production. The examples include the FlowCam macro (Sieracki et al., 1998), Video Plankton Recorder I and II (Batten et al., 2003), ZooSCAN (Gorsky et al., 2010), Underwater Vision Profiler (Picheral et al., 2010), and *in situ* Ichthyoplankton Imaging System (ISIIS) (Cowen and Guigand, 2008) and an onboard system (Colas et al., 2018). However, two identified main limits have high cost associated with operating the instruments, if not in the capital cost itself. The first one is that these organisms are often mixed with non-living particles in this size range. As such, the imaging process for coastal waters is extremely complex. The second limit is the quantity of data production, storage capacities, and analysis tools (Boss et al., 2018; Lombard et al., 2019). The development of shared statistical tools using computing science and artificial intelligence is the current direction to avoid an exponential increase of human resource requirement for data validation.

Organisms smaller than ∼20 μm (pico- to nano-meter range), which includes prokaryotes and protists, are too small for simple and cheaper optical imaging systems. Despite its higher cost, the use of flow cytometry (FC) with fluorescence triggers appears to be the simplest way to automatically access quantitative information of auto- and mixo-trophic cells (<20 μm) whereas measurements of heterotrophic cells are relatively less mature. Assessment of phytoplankton community structure using scanning flow cytometry (SFC) thus showed promising correlations between automated, high-frequency

Cost-effective *In Situ* Sensing Technologies

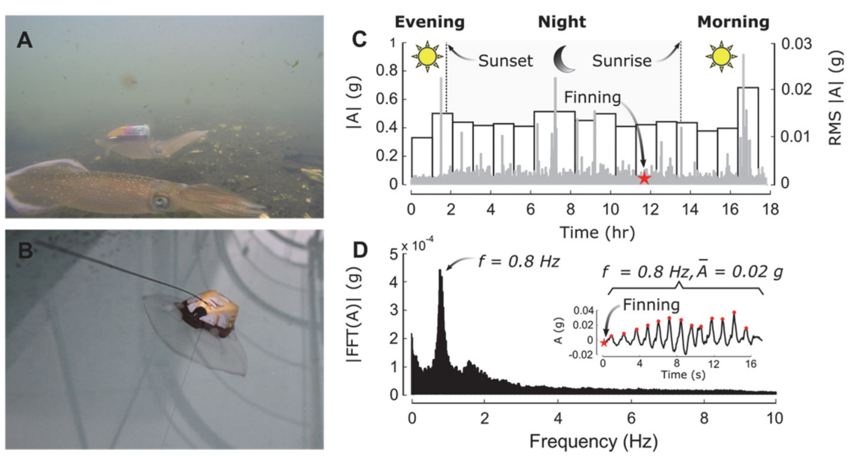

FIGURE 8 | (A) Squid with iTag, a novel biologging ecosensor (midground). A companion squid without an AnBS is seen in the foreground. **(B)** Jellyfish with a different iTag version. **(C–D)** iTag data showing general light evaluation from the light sensor, and movement patterns form the 3D accelerometer. Gray is instantaneous peak values and bars are 1 h RMS values. **(D)** A Fourier transform of accelerometer data showing the occurrence rates of the various accelerometer events with the star shown in the inset [adapted with permission from Mooney et al. (2015)].

in situ SFC measurements and proxies of community structure from remote sensing (e.g., Thyssen et al., 2015; Mouw et al., 2017). However, currently available commercial systems of SFC are generally bulky, power-hungry, and expensive. Similar to image analyses, the data processing still requires development of automatic clustering to avoid the high demand of human resources.

Despite the associated costs, some novel methods for automated *in situ* observations are in development by mixing FC and imaging capacities for microphytoplankton. As an example, the Imaging FlowCytobot (IFCB; Olson et al., 2003; Sosik and Olson, 2007; McLane Labs Inc., United States) is one of the most suitable and operational imaging systems for micro-plankton and phytoplankton observations. It is submersible and autonomous and has demonstrated applications as a sentinel for harmful algal taxa (Harred and Campbell, 2014). Underwater holographic systems, such as Holoflow@Sea "DHL" (Sun et al., 2008; Hermand et al., 2013, 2014), are also suitable for *in situ* imaging of organisms in the size range 2–200 μm and allow species identification and capture of dynamic underwater scenes at very fine scales. Several novel and lower cost methods for automated *in situ* observations at larger scale are currently in development (Karlson et al., 2017; Lombard et al., 2019). For example, the deployment of the FluoroProbe (Catherine et al., 2012) allows studying phytoplankton community composition at high spatial and temporal resolution, using a phytoplankton quantification method based on fluorescence excitation spectra. These developments of flow cytometers with imaging systems in the last decade represent an order of magnitude of cost reduction compared to traditional shipboard sampling and analysis.

Genetic Sensors for Microbes and eDNA

Many microorganisms perform crucial functions in biogeochemical cycling (e.g., methane or dimethylsulfide production, nitrogen transformations) and toxin production but are not optically distinct. Key groups of bacteria and archaea can only be monitored using analytical DNA and RNA techniques, resulting in the development of "microbe biomass and diversity" as an emerging EOV. Genetic sensors, also referred to as "Ecogenomic" Sensors, bring a wealth of analytical power to existing ocean monitoring instruments through *in situ*, autonomous detection and enumeration of specific DNA or RNA sequences, providing information on strain and species presence/absence, numbers and activities (Scholin, 2013; McQuillan and Robidart, 2017; Scholin et al., 2018). In cases where direct capture is not possible, the detection and population genetics of microbes, phytoplankton, zooplankton, and larger organisms can be acquired through their environmental DNA or "eDNA" (nucleic acids recovered from lysed or sloughed cells, feces, urine, gametes, mucus, etc.), offering a cost-effective, sensitive, and less invasive opportunity for monitoring organisms across the tree of life (Buxton et al., 2018).

The most advanced and only commercially available ecogenomic sensor is the Environmental Sample Processor (2nd Generation ESP; available through McLane Labs, Woods Hole, MA). The ESP has been demonstrated for monitoring fish (using eDNA signatures), fecal indicator bacteria, other prokaryotes, invertebrates and harmful algae from the water column in real time (Scholin et al., 2018). It is capable of measuring toxins and performing rRNA fingerprinting using ELISA and sandwich hybridization arrays, as well as qPCR using microfluidics (Doucette et al., 2009; Preston et al., 2009, 2011; Robidart et al., 2014). *In situ* preserved samples have been validated for DNA and RNA analyses, including metatranscriptomics (Ottesen et al., 2011). The ESP was recently deployed in Ocean Observing Buoys (Harmful Algal Bloom "HAB" buoy) in the Gulf of Maine Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) to validate the system for HAB monitoring. However, the up-front cost of such instrumentation is still prohibitively high for it to be widely deployed, despite the fact that ecogenomic sensors can potentially reduce the cost per sample by obviating the need for a specialist operator and decreasing the incidence of human error.

Critically, since they require small (μl scale) reagent volumes, molecular biological techniques are well-suited for miniaturized instrumentation. As an example of the path to a miniaturized system, the third generation ESP is smaller and less complex than the second, now fitting in the nose of a long-range AUV capable of Lagrangian drift (Pargett et al., 2015; **Figure 9**). Further reducing the size and complexity and improving the robustness of these instruments can significantly reduce operational costs associated with deployment and recovery. A rich innovation pipeline exists within academia and industry, including some key technological advances emerging from the medical "point of care" device sector to merge with miniaturized auto-samplers to advance environmental genetic sensor miniaturization, reducing instrumentation costs (Petralia and Conoci, 2017). Conformance to standards is required, and thus inter-calibration is required for each target organism, which will determine the extent to which these sensors are adopted by diverse sectors.

COMMON THEMES AND TRANSFORMATIVE FUTURE DIRECTIONS

The vision of this review is to identify strategies for breaking the high-cost barrier of ocean observing over the coming decade by developing cost-effective sensors and deployment strategies. While clear progress is already visible (e.g., as described in sections "Existing Cost-Effective Sensing Technologies for Biogeochemical EOVs and Relevant Parameters" and "Cost-Effective Deployments"), new approaches and technologies are still needed to achieve the order of magnitude increase in spatial and temporal resolution demanded to match the scales of ocean processes. In this final section, we summarize common strategies identified in the case studies presented above and consider how these lessons may recommend promising directions for moving forward toward increasingly cost-effective high resolution sensing of critical oceanographic variables.

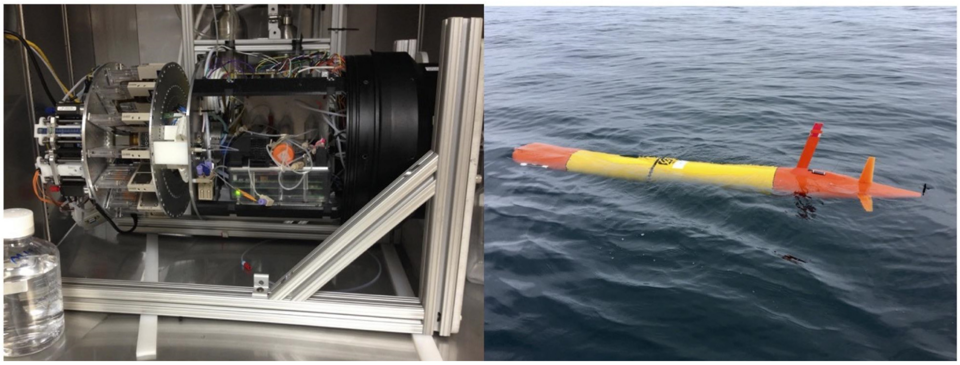

FIGURE 9 | The third Generation ESP fits into the nose of a Glider i.e., Long-Range Autonomous Underwater Vehicle (**left** photo courtesy of Bill Ussler; **right**, courtesy of Ben Raanan).

Common Strategies and Shared Challenges

To date, common characteristics of successful strategies for cost reduction and increasing data resolution are: (1) miniaturization, (2) use of lower priced materials, (3) innovative approaches for sensing, simultaneous detections, and multi-sensor integration, and (4) engagement of citizen scientists, stakeholders, and the public in deployments. Going beyond the aspects of sensing elements discussed above, there is also a range of other supplementary challenges that are common to all oceanographic sensors in which innovation has the potential to leapfrog progress. For instance, in contrast to typical surface-deployable sensors, packaging considerations for underwater sensors are critical for surviving the high pressure, corrosive environment, both for sensing elements and for the batteries, controllers, and associated peripherals. In recent years, some progress has been made in this area, in part driven by low-cost, hobby-grade robotics initiatives (e.g., low-cost pressure housings, such as those marketed by Blue Robotics[17]). However, there remains ample room for standardization in pressure housings and underwater connectors to promote further cost savings. Fouling, both physical and biological, must be considered in oceanographic deployments, and while a wide range of copper-based strategies and physical removal of fouling are in common use, there remains a critical need for innovative non-toxic approaches.

A further common challenge with oceanographic deployments is that the deployment platform places restrictions on the size and weight of the sensor. This can be mitigated by miniaturization of the sensors themselves or by further innovating the platform design itself. Advances to platform design may also allow for longer deployments and there is therefore a critical need for innovation in battery technologies and/or energy efficiency of sensors, as batteries typically represent the majority of the volume and weight of oceanographic deployments. Data collection and transmission by sensors may also be significantly limited by power consumption (see more discussion in section "Remaining Challenges: Power and Data Management").

[17] http://www.bluerobotics.com

Deployment Strategies

As the deployment of sensors can represent a large fraction of the cost of research, innovation in both platform design and deployment strategies play a critical role in enabling higher resolution data collection in ocean observing. Although professional deployments are critical to obtain high-quality data to study ocean biogeochemistry and biology, engagement of citizen scientists, stakeholders, and the public to deploy and use cost-efficient sensors is one emerging way to observe coastal environments on a much larger scale, and it is likely to accelerate as costs of sensors continue to drop. This includes the use of ships of opportunity, sail boats, fishing vessels (fisheries survey), and other private seagoing vessels as well as public/private coastal infrastructure (e.g., piers) as observing platforms for research and ecosystem monitoring (e.g., Doray et al., 2018). Citizen science may also bridge issues of data collection and dissemination to the public through integration with the growing "internet of things" connected by mobile apps and social media. Such strategies have the potential to simultaneously build public engagement in marine science research, resources management, and working toward long-term sustainability. Furthermore, as the number of deployed sensors grows, it may be possible to leverage co-located or proximate sensors to further improve data accuracy (i.e., reduce and better quantify uncertainty) relative to single-sensor deployments. Ultimately this may allow use of low-cost sensor "swarms" to collect data at a quality approaching that of high-cost scientific equipment. To maximize the output of citizen science, however, structured engagements, best practice guides, and practices for data quality control should be developed before the start of a deployment project.

Another novel and potentially cost-effective way of ocean observing is to use marine organisms as observing platforms. In addition to traditional tags deployed on large marine animals and fish species, small tags used on numerically dominant marine species, such as squid and jellyfish, are emerging as a result of sensor miniaturization and advancing of technologies;

this has the potential to tap into "unlimited" "bio-observing platforms" that can be deployed with *in situ* sensors in the ocean. As miniaturization of technologies continues, these tags can be used not only to study fine-scale behaviors of marine organisms but also to record key parameters of their surrounding physical and chemical environment. Because the environment sampled will be limited by the animals' behaviors, the community may need to explore methods for outfitting multiple species with different behaviors to observe a range of environments of interest.

Remaining Challenges: Power and Data Management

An overarching issue for deploying an increasing number of sensors and platforms is long-term power consumption (Brehmer et al., 2018) and data transmission. This issue may become exponentially more important as more sensors are deployed. In remote deployments where telemetry to shore via Wi-Fi is not an option, non-sensor costs may offset entirely the cost savings in sensor hardware. It is therefore essential that as cost-effective sensors continue to evolve the community consider strategic development of sensing nodes along with (i) networking and (ii) computational demands of the computational models the sensor data will be fed into. For example, sensors of the future could potentially locally process information, e.g., locally aggregate data via a mesh network to feed to an onboard instantiation of the target model, resulting in savings of energy and cost for data transmission by relaying only critical model outputs rather than raw data streams.

Onboard data fusion or feature extraction has already been carried out in many cases for detection of local threats (e.g., onset of harmful algal blooms). As power demand of processors continues to decrease faster relative to power demand for data transmission, local data processing will become increasingly advantageous. As artificial intelligence and data fusion techniques continue to be refined, the types of assessments that can be achieved *in situ* without losing accuracy or trustworthiness in data products will likely also expand. Such local sensing networks in remote deployments may have the capability to optimize observational assets and sampling strategies, as well as conduct calibrations without human input. If the community can forecast the types of such capabilities that will be most advantageous, we can identify promising pathways forward in underwater communication and networking (e.g., Leonard et al., 2007; Taya et al., 2018; Song et al., 2019) and data fusion (already used for above-water radar applications like (Guerriero et al., 2010).

Roadmapping: Accelerating Transfer of New Technologies to Users

Roadmapping, which has been successfully applied in other fields such as energy systems planning, enables prediction and planning of future characteristics and technologies of complex systems. Recent attempts have jump-started this activity for biogeochemical sensing in ocean observing systems (AtlantOS EU H2020 project, task 6.1[18]), contacting biogeochemical sensor and instrumentation technology developers across the globe and requesting their inputs to chart the (projected) availability of instruments over the next decade. Contributors are encouraged to provide links to technical characteristics of the technology and to give a timetable for development of the technology using the TRL framework, with the intention to give ocean technology developers and ocean observers the ability to predict and to plan for the timely use and uptake of state of the art technologies.

To achieve this vision, however, the road mapping needs to be integrated with ocean observing governance entities such as GOOS, JCOMM, and GEO. In addition, it requires frank engagement from the technology development community, which must be promoted by a sense of buy-in from the ocean observing community; this will also incentivize developer involvement through commercial success of products that are a response to the roadmap. The authors hope that this review will drive individuals in the field to consider potential uses for lower-cost sensors in the coming decades and contribute to this roadmap.

Challenges related to road mapping include concerns around disclosure of intellectual property or strategic development plans in what is an increasingly competitive landscape, particularly from the side of industry. However, evidence to date is that developers are keen to reveal their development plans to aid uptake and that the international observing governance bodies are ready and willing to support and sustain this activity beyond the life of short term individual projects (see footnote 18). There is also evidence that inclusion in the roadmap is aiding developers of instrumentation through promoting links to platform and observing systems (see footnote 18). Once new instruments are made available, information databases, such as the one maintained by the Alliance for Coastal Technologies,[19] will be critical in linking global customers to an increasing array of options for studying marine systems.

CONCLUSION

Further development of cost-effective sensing technologies and deployment strategies can offer innovative solutions and strengthen the observing capabilities to respond to the growing needs for marine biogeochemistry, biology, and ecosystem observation, to inform marine resource management, to ensure the durability of ecosystem services, and to monitor and study global change impacts. A shift toward ocean observing technologies that are significantly lower in cost means new high-resolution applications can be targeted. It is clear that many useful cost-effective biogeochemical sensors are available or will soon become available, and that biological *in situ* sensors require more attention from the ocean science community and funding agencies in the coming decade to reduce the gap. It is also evident that cost benefits scale when integrated

[18]https://www.atlantos-h2020.eu/download/deliverables/6.1%20Sensors%20and%20Instrumentation%20Roadmap.pdf

[19]http://www.act-us.info

with other traditional and non-traditional deployment strategies. As more sensors can be deployed, we will move from a single point sensor to having arrays of sensors for broader spatial and temporal scale measurements. This will also lead to market scale availability, opening up the possibility for a more diverse group of global scientists and citizen scientists having access to sensors and aiding in the democratization of ocean science.

In closing, we challenge the ocean observing community to consider exploring new ways to fund the ever-growing ocean observing enterprise, particularly those that tie in with new avenues for deployment and inclusion of stakeholders and the community in the scientific endeavor. Traditional routes of research funding may be important but insufficient to support the growing needs of ocean observing, and commercialization of new technologies may have limitations, largely depending on commercial demand and profits. Alternatively, crowd-funding may have the potential to grow significantly if engagement of citizen science using cost-effective sensors grows. In turn, increasing demand for more sensors from non-traditional or non-academic communities, such as citizen scientists, resource management entities, and environmental monitoring groups, may help to reduce the cost of commercialization of a technology.

AUTHOR CONTRIBUTIONS

ZW led this effort, and contributed to most parts of the work and revision and response to reviewers' comments. HM co-led the initial initiative of this work, contributed to the biological part of the work, overall structure, and manuscript revision. AVM co-led the initial initiative of this work, contributed to the nutrient sensor section and substantially to the "Future Directions" section, as well as revision, framing, and editing of the complete manuscript. APM co-led the initiative of this work, contributed substantially to the sections "Existing Cost-Effective Sensing Technologies for Biogeochemical EOVs and Relevant Parameters" and "Common Themes and Transformative Future Directions" as well as revision, framing the complete work in addition to final manuscript editing. MM contributed to the sections related to the LOC technology (sections "Dissolved Oxygen," "The Carbon Dioxide (CO_2) System," "Nutrients," and "Designing Cost-Effective Deployments With Miniaturized Sensors") and roadmapping (section "Roadmapping: Accelerating Transfer of New Technologies to Users"). BG contributed to the section "Democratizing Access to Ocean Observing Technology." TM contributed to the sections "Animal Oceanographers" and "Common Themes and Transformative Future Directions" and revision of the manuscript. WM contributed to the sections "Underwater Bio-Acoustics" and "Optical Sensors for *in situ* Plankton Monitoring" on bio-acoustic and optic sensors. JM contributed to the section related to microbes and eDNA, and revision of the manuscript. JR contributed to the section "Genetic Sensors for Microbes and eDNA" related to genetic sensors and revision of the manuscript. JC contributed to the section "Suspended Particles and Particulate Organic Carbon" on sensor technologies for particles and POC, and revision of the manuscript. MS contributed to the sections "Optical Sensors for *in situ* Plankton Monitoring" and "Common Themes and Transformative Future Directions," and revision of the manuscript. AD contributed substantially to the section related to Fluorescence and Chlorophyll-*a*, and revision of the manuscript. AS contributed to sections "The Carbon Dioxide (CO_2) System," "Nutrients," and "Designing Cost-Effective Deployments With Miniaturized Sensors," and revision of the manuscript. SM contributed to the section "The Carbon Dioxide (CO_2) System" and revision of the manuscript. KF contributed to the section "Genetic Sensors for Microbes and eDNA" on eDNA. PB co-led the initial initiative of this work, and contributed to the biological parts of the manuscript, and the manuscript revision.

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frontiers in Marine Science

REVIEW
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Challenges for Sustained Observing and Forecasting Systems in the Mediterranean Sea

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The Mediterranean community represented in this paper is the result of more than 30 years of EU and nationally funded coordination, which has led to key contributions in science concepts and operational initiatives. Together with the establishment of operational services, the community has coordinated with universities, research centers, research infrastructures and private companies to implement advanced multi-platform and integrated observing and forecasting systems that facilitate the advancement of operational services, scientific achievements and mission-oriented innovation. Thus, the community can respond to societal challenges and stakeholders needs, developing a variety of fit-for-purpose services such as the Copernicus Marine Service. The combination of state-of-the-art observations and forecasting provides new opportunities for downstream services in response to the needs of the heavily populated Mediterranean coastal areas and to climate change. The challenge over the next decade is to sustain ocean observations within the research community, to monitor the variability at small scales, e.g., the mesoscale/submesoscale, to resolve the sub-basin/seasonal and inter-annual variability in the circulation, and thus establish the decadal variability, understand and correct the model-associated biases and to enhance model-data integration and ensemble forecasting for uncertainty estimation. Better knowledge and understanding of the level of Mediterranean variability will enable a subsequent evaluation of the impacts and mitigation of the effect of human activities and climate change on the biodiversity and the ecosystem, which will support environmental assessments and decisions. Further challenges include extending the science-based added-value products into societal relevant downstream services and engaging with communities to build initiatives that will contribute to the 2030 Agenda and more specifically to SDG14 and the UN's Decade of Ocean Science for sustainable development, by this contributing to bridge the science-policy gap. The Mediterranean observing and forecasting capacity was built on the basis of community best practices in monitoring and modeling, and can serve as a basis for the development of an integrated global ocean observing system.

Keywords: observing and forecasting systems, sustained observations, ocean variability, FAIR data, climate, operational services, science with and for society, SDG's

Abbreviations: ADCP, Acoustic Doppler Current meter Profiler; Argo, Global array of subsurface profiling floats; BiOS, Bimodal Oscillation System; CALYPSO, Coherent Lagrangian Pathways from the Surface Ocean to Interior; CMEMS, Copernicus Marine Environment Monitoring Service; CAPEMALTA, Meteo and marine operational forecasting system for the Maltese Islands; CTD, Conductivity Temperature Depth; CYCOFOS, Cyprus Coastal Ocean Forecasting System; EOV, Essential Ocean Variable; EU, European Union; CO_2, Carbon dioxide; CSIC, Spanish National Research Council; DEKOSIM, Center for Marine Ecosystems and Climate Research; EMODnet, European Marine Observation and Data Network; EOOS, European Ocean Observing System; EuroGOOS, European Global Ocean Observing System; FAIR, Findable, Accessible, Interoperable, Re-Usable; FB, Ferrybox system; GCOS, WMO Global Climate Observing System; GEO, Group on Earth Observations; GitHub, A web-based hosting service for software development projects that use the Git revision control system; GIS, Geographic Information System; GOOS, Global Ocean Observing System; GTS, Global Teleconnection System; ICCAT, International Commission for the Conservation of Atlantic Tunas; IEO, Spanish Institute of Oceanography; IEOOS, IEO Observing system around Spanish mainland, the Canary and the Balearic Islands; Ins-TAC, the *In Situ* Thematic Assembly Center; IOC, Intergovernmental Oceanographic Commission of UNESCO; IODE, IOC International Oceanographic Data and Information Exchange; IPCC, International Panel Climate Change; ISO, International Standards Organization; IOLR, Israel Oceanographic & Limnological Research; ISRAMAR, Israel Marine Data Center; LDCs, Least Developed Countries (LDCs); MAOS, Mobile Autonomous Oceanographic Systems; MARIA, Atmospheric and wave forecasting system for the Sicilian Channel; Med-Argo, Argo Regional Center for the Mediterranean; Med-MFC, CMEMS Mediterranean Monitoring and Forecasting Center; MONGOOS, Mediterranean Oceanography Network for Global Ocean Observing System; MOOSE, Mediterranean Ocean Observing System for the Environment; NODC, National Oceanographic Data Centers; ODYSSEA, Operating a Network of Integrated Observatory Systems in the Mediterranean Sea; PORTUS, *Puertos del Estado (in Spanich)* System; POSEIDON, HCMR monitoring and forecasting system; QA/QC, Quality Assurance/Quality Control; RADMED, *Radiales Mediterráneo (in Spanish);* REMPEC, Regional Marine Pollution Emergency Response Center for the Mediterranean Sea; RITMARE, Ricerca ITaliana per il MARE; ROOS, Regional Ocean Observing System; ROSARIO, Malta shelf thermo-hydrodynamic forecasting sysyem; R/V, Research Vessel; SAMOA, *Sistema de Apoyo Meteorológico y Oceanográfico a las Autoridades portuarias in Spanish.*; SANIFS, Southern Adriatic Sea and Northern Ionian Forecasting System; SeaDataNet, Pan-European infrastructure for ocean and marine data management; SE LB, South Eastern Levantine Basin; SDG(s), Sustainable Development Goal (s); SDG14, Sustainable Development Goal 14: Life below the sea; SDG13, Sustainable Development Goal 13: Climate action; SeaDataCloud, Further developing the pan-European infrastructure for marine and ocean data management; SELIPS, South

INTRODUCTION

The Mediterranean Sea is an ideal laboratory for studying ocean processes of global relevance, such as water mass formation, overturning circulation, boundary currents, meso/submesoscale eddies and instabilities, carbon export and associated ecosystem responses (Pinardi et al., 2006; Malanotte-Rizzoli et al., 2014). The Mediterranean is one of the most vulnerable regions in the world due to the impacts of climate change (e.g., alterations in the overturning circulation; extreme wave heights and warming, sea level rises, storm surges, acidification, oxygen depletion, invasive species, etc.), and its precarious socio-economic conditions and fragile political systems, particularly in more vulnerable southern shore countries.

From a societal perspective, stakeholders across the Mediterranean Sea (harbors and marinas, fisheries and aquaculture, oil companies, maritime transport, civil protection, tourist resorts, environmental agencies, research institutions, citizen associations, etc.) are already aware of the potential benefit of establishing an ocean observing and forecasting system. Establishing a sustained Mediterranean system is therefore timely and stakeholders have already recognized the importance of embracing the entire value-adding ocean chain, from observations to forecasts and customized products, thus providing the foundations for a sustainable Blue Economy compliant with the UN's Sustainable Development Goals (SDG).

The Mediterranean research community has organized several programmes and projects to develop the end-to-end system, which will contribute mainly but not only to the UN SDG13 (Climate Action) and SDG14 (Life Below Water) goals and the Sendai Framework for Disaster Risk Reduction. A good example is the well-established Mediterranean modeling system, which is structured around the Copernicus Marine Environment Monitoring Service (CMEMS) and national and sub-regional downscaled forecasting systems, with numerous high-quality applications providing user-oriented services. In addition, advanced multi-platform and integrated observing systems are continually being developed and implemented by universities, research centers, European research infrastructures and private companies facilitating mission-oriented innovation that feeds into CMEMS (Le Traon et al., 2019) and the EMODnet programme (Martín Miguez et al., 2019).

Thus, the community can respond to science priorities, societal challenges and stakeholders needs, developing a variety of fit-for-purpose products. The combination of state-of-the-art observations and forecasting models provides new opportunities for downstream services in response to the needs of the heavily populated Mediterranean coastal areas. However, the observing and forecasting system has various deficiencies and shortcomings, such as:

- The lack of sustained *in-situ* observations for several Essential Ocean Variables (EOVs) and sometimes poor data policy, particularly in the Central-Eastern Mediterranean and on the Northern African coasts.
- The diversity of the forecasting models is limited and their skills have not been fully assessed yet;
- There is little connection between the development of the satellite observing system and situ components, which is in many instances hampering the opportunity to extend the range of observables from space. Satellite observations cover the entire Mediterranean but only provide surface information and at scales that are not of high enough resolution to capture the fine-scale processes that characterize the high temporal and spatial variability of this basin.
- Existing networks are only supported by national research funds and their long-term sustainability is at risk. Coordination and basin-scale integration is difficult, particularly across-disciplines (e.g., fishery data collection vs. physics and biogeochemistry).
- Communication with the wide range of regional policy stakeholders is generally lacking and requires development.

The Mediterranean observing and forecasting systems are part of a larger ocean value chain that links observations to applications of societal benefit. This value chain can be subdivided into the "basic" or "core" systems/services, which are mainly related to observations and forecasting products/infrastructures, and "downstream" services that generate customized products for policy makers, industry and the general public. The "basic" infrastructure is essential for the downstream services, and it must run smoothly and have a fully open and free data policy.

The aim of this paper is to review the current status of the Mediterranean Sea environmental and climate challenges and document the present observing and forecasting system organization and the downstream services, resulting in an analysis of the gaps and deficiencies. Solutions are then proposed, with a special focus on the challenges to be faced over the next decade. In section Mediterranean Sea Environmental and Climate Challenges, the major Mediterranean Sea environmental and climate challenges are discussed, and the basic systems including the Mediterranean Oceanography Network for Global Ocean Observing System (MONGOOS) collaborative framework are presented in sections Basic Systems and Services and MONGOOS Collaborative Framework. Section Downstream Services in Response to Societal Challenges and Stakeholders provides examples of the downstream services in place. Section Gaps and Prospects for the Next Decade gives a description of the gaps and future actions, and section Conclusions concludes.

MEDITERRANEAN SEA ENVIRONMENTAL AND CLIMATE CHALLENGES

In the last few decades, anthropogenic pressures (e.g., climate change, local pollution, tourism, fisheries, maritime transport, etc.) on the Mediterranean ecosystems have increased. As a consequence, significant and likely irreversible changes are

Eastern Levantine Israeli Prediction System; SISCAL, Satellite-based Information System on Coastal Areas and Lakes; SISMER, *Systèmes d'informations scientifiques pour la Mer (in French);* SKIRON, Operational Atmospheric Forecasting System; SOCIB, Balearic Islands Coastal Ocean Observing and Forecasting System; SST, Sea Surface Temperature; SeaDataNet, Pan-European infrastructure for ocean & marine data management; SWOT, Surface Water and Ocean Topography; TAC, Thematic Assembly Center; WMO, World Meteorological Organization; WAM, Wave Model; WRF, Weather Research and Forecast atmospheric Model.

occurring in Mediterranean waters including the warming of deep waters, increased anthropogenic carbon dioxide inputs and uptake, acidification and biodiversity loss. Such factors are severely damaging the ecosystems in surface and intermediate/deep waters and marine habitats as a whole.

The recent Ocean State Report from the Copernicus Marine Environment Service (von Schuckmann et al., 2018) stated that the sea surface temperature between 1993 and 2016 in the Mediterranean has increased by $0.04 \pm 0.004°C$ per year, which is the second largest trend in the European regional seas after the Black Sea. Sea surface salinity also increased 0.01 PSU per year average over the whole basin in the same time period. The sea level has increased by 2.7 ± 0.9 mm per year, comparable to the increase in the North West Shelf and Black Sea but less rapidly than the Baltic Sea and the global ocean, probably due to the salinity trend and the hydrological cycle changes but also to the specific semi-enclosed nature of the basin (Pinardi et al., 2014).

The Mediterranean Sea has also been identified as an important anthropogenic carbon pool where the column inventory is much higher than in the Atlantic (Álvarez-Berastegui et al., 2016; Schneider et al., 2018). This is due to its intrinsic physico-chemical characteristics, in which warm and highly alkaline waters are prone to absorb high amounts of CO_2 from the atmosphere and transport it to deep waters via a number of convective areas. However, the variability of inorganic carbon remains unknown, given the lack of observations of the carbonate system at present. While at the global scale CMEMS models simulate a relatively stable ocean carbon uptake during the 1990s and a sharp increase since the beginning of the 2000s, the Mediterranean Sea appeared to act as a weak sink over the last decade (-3.5 gC/m^2/year in 2016, von Schuckmann et al., 2018).

The time-mean circulation is now well known (**Figure 1**) from both reanalysis and observations (Rio et al., 2014; Pinardi et al., 2015; von Schuckmann et al., 2016). It is composed of multiscale structures, such as basin-scale gyres, intensified boundary currents, open ocean intensified jets and recurrent and reversing gyres (Font et al., 1988; Poulain et al., 2007; Pinardi et al., 2015). A well-documented intense climatic event occurred in the nineties, the so-called Eastern Mediterranean Transient (EMT, Klein et al., 1999), which radically changed the deep-water properties of the basin. This is the only event of its kind, captured during a basin-scale survey carried out in the 1990s. The change involved a reversal of the Northern Ionian Sea circulation, also called the Adriatic-Ionian Bimodal Oscillation System (BiOS, Gačić et al., 2011), which was found to be correlated to wind stress curl changes (Demirov and Pinardi, 2002; Nagy et al., 2019). These changes are specific to the Mediterranean Sea and had a significant impact on the ecosystem functioning at the basin scale (Danovaro et al., 2001).

In the Western Basin, a second climatic anomaly known as the Western Mediterranean Transient (Schroeder et al., 2016) began between 2004 and 2006 during very cold winters. It was induced by intense heat flux losses and deep water formation in the Gulf of Lion (Schroeder et al., 2008), leading to an abrupt increase of temperature and salinity in deep waters and thus accelerating the trends observed over the past 40 years (Borghini et al., 2014). It also resulted in an anomalous stratification of the deep-water column due to the superposition of newly formed warmer and saltier deep waters (Schroeder et al., 2016). The outflow of these waters through the Strait of Gibraltar is detectable in late winter-early spring (García-Lafuente et al., 2011; Sammartino et al., 2015) and it was clearly identified a decade later (Naranjo et al., 2017). Repeated glider missions along the Ibiza Channel endurance line have provided key semi-continuous observations, from which the variability of the meridional exchanges in the Western basin and its relation to surface and intermediate water mass changes can be monitored (Heslop et al., 2012; Juza et al., 2019).

From a biogeochemical point of view, the Mediterranean Sea has relatively high O_2 concentrations in deep waters, caused by intense ventilation mechanisms resulting from winter deep ocean convection processes (Schneider et al., 2018). In the intermediate layer occupied by the Levantine Intermediate Water (LIW), a minimum oxygen layer (OML) is present throughout the Mediterranean Sea. With global warming, these concentrations have become very sensitive to an overall decrease in O_2, as predicted by climate and biogeochemical models, particularly in response to an increase in water column stratification (Oschlies et al., 2008). However, the energetics of the basin circulation have recently been studied and it was found that both buoyancy and wind inputs contribute to invigorating the total energy of the circulation, thus providing evidence of the basin's intrinsic resilience to de-oxygenation processes (Cessi et al., 2014). In the past the Mediterranean is known to have been prone to large deoxygenation events, known as sapropels (Negri et al., 2009).

The N/P ratios in the Mediterranean deep waters are higher than in the global ocean (about 24:1 vs. 16:1) with a marked horizontal gradient from west to east (Bethoux et al., 2002). This is explained by a preference for phosphate consumption over nitrate by phytoplankton, indicating a phosphate limitation, particularly in the eastern basin (Thingstad et al., 2005; Pujo-Pay et al., 2011). More recent studies have highlighted the significant contribution of anthropogenic inputs of (N,P) through the atmosphere and rivers to surface and intermediate waters in the Mediterranean (Cossarini et al., 2012), and a high variability of surface nutrients related to the variability of the mixed layer depth, particularly in the Western basin (Pasqueron de Fommervault et al., 2015). The Mediterranean is also known to be an oligotrophic basin with some intermittent bloom regions (D'Ortenzio and Ribera d'Alcalà, 2009; Mayot et al., 2017) but the general trend is not clear. Some future scenarios predict an increase of nutrients gradients whereas others suggest a homogenization of bio-regions toward oligotrophy or eutrophication (Lazzari et al., 2014; Colella et al., 2016).

Basin wide, the Mediterranean Sea is a region of significant fronts, mesoscale and submesoscale variability (Pascual et al., 2013; Bosse et al., 2017; Testor et al., 2018), which regulate the exchanges between the open sea, the shelves and the coastal areas (Pinardi et al., 2006; Jordi et al., 2008) although at smaller scales than in other parts of the global ocean, given the Sea's small Rossby radius (Escudier et al., 2016b; Barcelo-Llull et al., 2019). Such mesoscale-submesoscale variability (McWilliams, 2016) drives the vertical exchanges between the upper layers and

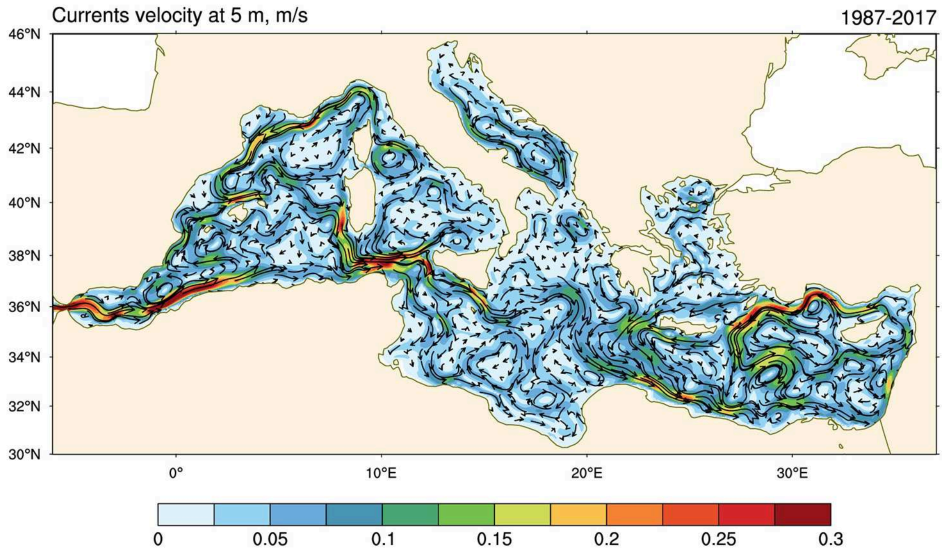

FIGURE 1 | The time mean circulation from CMEMS reanalysis (period 1985–2017, product MEDSEA_REANALYSIS_PHYS_006_004). The velocity field is visualized by curved arrows overlaying the amplitude of the currents (m/s) in color. The detailed description of this circulation picture is offered in Pinardi et al. (2015) and an update is given in von Schuckmann et al. (2016).

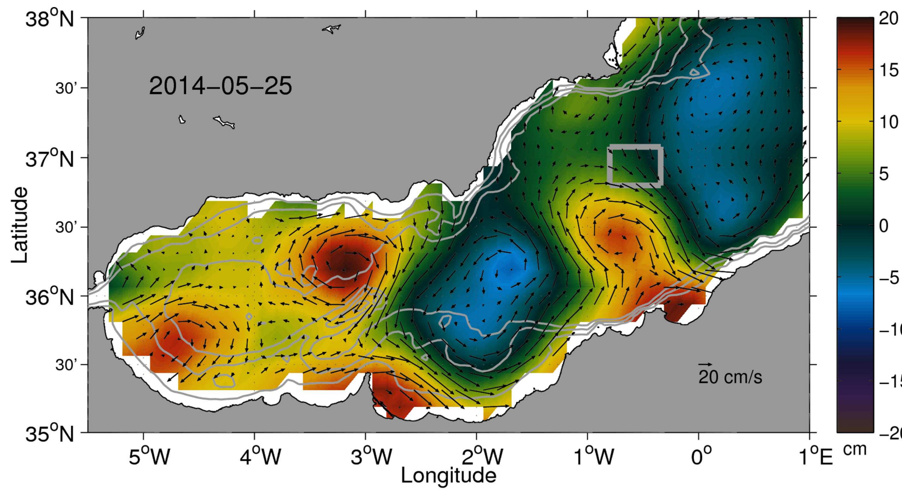

FIGURE 2 | Absolute dynamic topography and associated geostrophic currents for 25 May 2014 derived from gridded altimetry fields (CMEMS). The gray box corresponds to the domain sampled during the AlborEx experiment in the eastern Alborán Sea aimed at understanding meso- and submesoscale processes in an intense front [from Pascual et al. (2017)].

the deep ocean (**Figure 2**, Tintoré et al., 1991; Pascual et al., 2004; Ruiz et al., 2009) and in particular the supply of nutrients to the euphotic zone (Mahadevan, 2016; D'Asaro et al., 2018). Given the ideal conditions of the Alborán Sea in the Western Mediterranean (Ruiz et al., 2009, 2018; Pascual et al., 2017) the international programme CALYPSO[1] was established in 2018 to provide an understanding and predictive capability of the three-dimensional coherent pathways by which water carrying tracers and drifting objects is transported from the surface ocean to depths below the mixed layer.

[1]https://calypsodri.whoi.edu

The heat and drought waves are also major challenges in terms of the water availability and preservation of marine ecosystems in the Mediterranean (Vautard et al., 2007). The risk of extreme heat waves in Europe, like the unprecedented event in the summer of 2003, is likely to increase in the future, and requires further understanding of their potential predictability and possible mitigation. Extensive mass mortality in benthic communities was registered after the 2003 heat event (Olita et al., 2007; Garrabou et al., 2009) and heat waves are now understood to boost harmful algal blooms (HAB) (Joehnk et al., 2008). There is also a general concern that jellyfish are becoming more prevalent in many regions around the Mediterranean Sea

(Shiganova et al., 2001; Kogovsek et al., 2010; Prieto et al., 2015). Jellyfish have a significant impact on coastal economic activity and on the important tourism industry of the Mediterranean region (accounting for 15% of global tourism) (Ciscar et al., 2001), but no systematic, scientific based monitoring system at basin scale has been implemented (Prieto et al., 2015).

The sustainability of marine living resources is also a major challenge in the Mediterranean. Most of the fish stocks (78%) monitored by the General Fisheries Commission for the Mediterranean are overexploited (FAO 2018). Sustained monitoring could play a key role in knowledge-based fisheries management and ecosystem conservation. The recovery of the Eastern Atlantic bluefin tuna population during the last decade, after a long period of continuous and alarming decrease, is a successful example of how science and operational oceanography can trigger advances in the sustainability of fisheries and species conservation. At SOCIB, the combination of hydrodynamic models, remote sensing and *in situ* data has enabled the development of techniques for predicting both the spawning and larval habitat distribution, and the survival rate of the egg and larvae in the Balearic Sea (Álvarez-Berastegui et al., 2016; Reglero et al., 2018). These novel predictive capabilities have been applied to the standardization of larval abundance indices used to evaluate the trends of adult tuna populations during the last two decades (Ingram et al., 2017; Álvarez-Berastegui et al., 2018a), and to integrate environmental variability into the short-term forecasting of the survival of larvae and the derived immature individuals. The International Commission for the Conservation of Atlantic Tunas (ICCAT) applies these methods to establish the annual fishing quotas for bluefin tuna and Mediterranean albacore tuna.

The Mediterranean Sea is also affected by tsunami-frequency sea level changes, which are not triggered by seismic activity but driven by air-pressure disturbances that are often simultaneous to fast-moving perturbations, such as thunderstorms, squalls, and other storm fronts. These episodes, called meteo-tsunamis (e.g., Vilibic et al., 2016), have been reported in Croatia, the Balearic Islands, Sicily, Malta and Greece. Specifically, Croatian islands and Menorca are where the highest magnitudes of meteotsunamis have been observed worldwide (6- and 4-m oscillations, respectively). Meteotsunamis generate flooding and are associated with very strong currents (up to 4 m/s), cause serious economic damage to ships and harbor installations and can travel long distances and influence a very long area of coastline (Masina et al., 2017; Picco et al., 2019).

Floating plastic pollution tend to concentrate on convergences acting as retention areas and in eddies and fronts at lower scales (Maximenko et al., 2012). In a recent study based on numerical simulations of plastic transport, Liubartseva et al. (2019) identify the potentially most polluted areas in this Sea from a series of anthropogenic sources, which confirm that the highest concentration of plastic is found near continental shores (Collignon et al., 2014; Ruiz-Orejón et al., 2016, 2018). Information is still limited but Eriksen et al. (2014) estimated floating plastic debris in the Mediterranean as 23,150 tons, with 3,056 corresponding to micro- and nano-plastics, which mirrors the 1,500 tons estimated from samples obtained by Ruiz-Orejón et al. (2016). Biodiversity is highly affected by marine litter, either through entanglement, ingestion or colonization (Deudero and Alomar, 2015; Fossi et al., 2018). There is even a certain overlap between the feeding areas of diverse marine species and the convergence zones of floating microplastics (Fossi et al., 2017). Thus, observing and forecasting systems are essential in providing tools to understand the effects of plastics on species and ecosystems and to achieve the Good Environmental Status (GES) as set out in the European Marine Strategy Framework Directive (MSFD) (Galgani, 2019). The hazard mapping recently conducted by Compa et al. (2019a), which correlates litter with species distribution maps in the Mediterranean basin, is an interesting approach. Other potential observing systems for marine litter are the cleaning coastal vessels that provide densities, distribution and temporal patterns of floating marine macrolitter along coastal systems such as in the Balearic Islands (Compa et al., 2019b).

All these issues require a scientific basis for the understanding, monitoring and modeling of the Mediterranean Sea marine environment, and a collaborative international framework to design and implement the basic services in support of the downstream sector. The existing monitoring and forecasting system that have been developed over the past 20 years for operational oceanography need to be expanded to biochemical EOVs, and toward applications that will offer solutions for climate mitigation and adaptation, biodiversity conservation, decreased ocean pollution and more accurate met-ocean forecasts for disaster risk reduction.

BASIC SYSTEMS AND SERVICES

As described in the introduction, basic systems produce "generic" products ready to be ingested by downstream services. The basic system infrastructure is composed of observing systems, forecasting and data assembly systems. In the following we describe each component in the Mediterranean Sea basic infrastructure.

Multi-Platform Observing Systems

Most of the present European regional observing systems described in this section have their origin in the coordinated efforts that started in the early nineties in the Mediterranean Sea, due to EU strategic planning and associated funded projects. This has led to a well-structured and reasonably coordinated community that feeds real-time and delayed mode quality-controlled data into the different European portals, in particular through the CMEMS Mediterranean Monitoring and Forecasting Center (Med-MFC), the *in situ* Thematic Assembly Center (Ins-TAC, Petit de la Villeon et al., 2018) and EMODnet. However, the funding for the observing components is in most cases of only national origin and the sustainability of these key initiatives is a critical issue and an important concern.

MOOSE

In 2010, a Mediterranean Ocean Observing System for the Environment (MOOSE[2]) was implemented in France as an integrated observing network of the NW Mediterranean Sea.

[2]http://www.moose-network.fr

MOOSE objectives include the detection and identification of environmental anomalies via both long-term monitoring and near real-time measurements capabilities.

The MOOSE strategy is based on multisite and multi-platform continuous observations from the coast to the deep sea. It combines Eulerian observatories and autonomous Lagrangian platforms to collect the EOVs and is open to new approaches based on omics and modern imagery techniques, which can better address the emerging issues in marine ecology. It is designed to detect and monitor seasonal or inter-annual variability, and the impact of extreme events that control physical and biogeochemical fluxes and marine biodiversity. MOOSE also provides a large flow of real-time data to facilitate the validation of operational oceanographic models. The MOOSE strategy is based on an *in-situ* observing system, capable of capturing all scales of variability, thus avoiding any aliasing effects caused by sub-sampling. Thus, MOOSE aims to address scales of variability ranging from the very small (1 km horizontally, over a few days) to the basin scale (500 km, months/years), passing by the mesoscale (15 km, weeks/months). The MOOSE components are (**Figure 3**):

- Two river observatories (Rhône, La Têt)
- Three observatories for atmospheric deposition (Cap Béar, Frioul, Cap Ferrat)
- Two moorings in canyons (Lacaze-Duthiers, Planier), which are complimented by three open sea moorings from EMSO network (Lion, Dyfamed, and Albatross)
- Two HF radars (Toulon, Nice)
- Monthly and annual ship visits (Mola, Antares, Dyfamed, and MOOSE_GE)
- Two glider endurance lines along the north-south sections (Marseille-Minorca, Nice-Calvi)

Marine observations are accomplished by combining observations from fixed (deep moorings and buoys) and Lagrangian platforms (Argo floats and gliders) which are completed with ship surveys both in the coastal and open sea regions. In the MOOSE network, two glider endurance lines are currently in operation: Villefranche-Dyfamed-Calvi and Marseille-Lion-Menorca.

Deepwater convection processes and their interaction with dense shelf water cascading events modify deepwater mass properties and deep sediment resuspension in the Gulf of Lion (Durrieu de Madron et al., 2013). Over the past decade, the MOOSE network has documented a slow increase in deepwater temperature, punctuated by very rapid warming, leading to even warmer and saltier deep waters. The absence of intense convection reinforces the oxygen minimum signature in the intermediate waters, especially in the Ligurian Sea where the winter mixing and ventilation are less intense than in the Gulf of Lion (Coppola et al., 2018).

Regular and long-term monitoring in the MOOSE network has provided significant results that can be used to interpret the temporal variability of nutrients and the zooplankton community, which are sensitive to deep vertical mixing events (Donoso et al., 2017). Coastal observations showed that the long-term evolution of nutrient inputs here is driven by Rhône River water discharges, which respond differently depending on whether a climatic or an anthropogenic forcing occurs (Cozzi et al., 2018).

SOCIB

The Balearic Islands Coastal Ocean Observing and Forecasting System (SOCIB[3]) is a Marine Research Infrastructure, a multi-platform and integrated ocean observing and forecasting system that provides streams of data, added value products, and forecasting services from the coast to the open ocean (Tintoré et al., 2013). It was initiated in 2008 and since 2014 it is included in the Spanish Large-Scale Infrastructure Map. SOCIB aims to characterize ocean state and variability at different scales, from local to submeso-mesoscales and from nearshore and regional to large basin scales, on temporal ranges that span from events to climate.

Figure 4 shows the SOCIB network of observing infrastructures for long-term monitoring and for dedicated deployment during open access intensive multi-platform process-oriented studies. The network includes satellite-tracked surface and profiling drifters (through an annual deployment of 3 Argo floats[4] and 8 SVP drifters), 16 autonomous fixed coastal stations deployed around the Balearic Islands, 2 met-ocean moorings located in the Ibiza channel and the bay of Palma, a 24 m coastal research vessel, 2 high-frequency radar stations overlooking the Ibiza Channel, a fleet of 7 autonomous underwater gliders and 2 beach monitoring stations. More specifically, SOCIB runs a glider endurance line in the Ibiza channel (a well-established biodiversity hot spot) to monitor the north-south exchanges and their relation to the variability of the circulation, of the different water masses and the associated ecosystem variability. Animal-borne instruments are a new addition to SOCIB and since 2015, tracked sea turtles complement the observing system with unique and cost-effective data (Patel et al., 2018) providing information on essential biodiversity variables and contributing to knowledge based marine conservation (Boehme et al., 2009). Complementary to this quasi-real time network, high-resolution beach bathymetries and sediment samples surveys, multidisciplinary seasonal oceanographic surveys in the Ibiza and Mallorca Channels and glider sections to Algeria and Sardinia are performed periodically, providing long-term observations that allow quantification of the variability, changes and trends in beach morphology, water mass transformation, mass and heat transport and content, eddies structure and variability, etc.

All SOCIB data are made available in near real time for scientists and society under the terms of an open access policy, in line with European initiatives such as Jericonext (Farcy et al., 2018). The data, scientific production, outreach and engagement activities, as well as tools and products developed are a clear performance indicator of SOCIB achievements and innovations in the new era of ocean observation. The alignment of these elements is possible due to a dedicated data lifecycle management that is fully committed with the Findable,

[3] www.socib.es
[4] Contribution to EuroArgo ERIC.

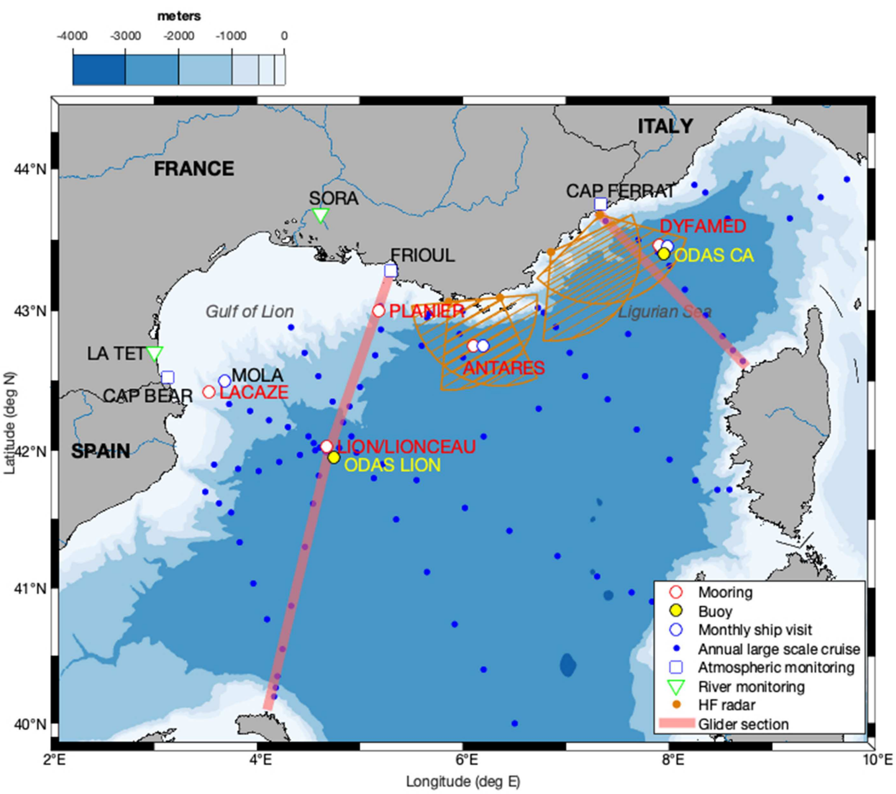

FIGURE 3 | The MOOSE observatory components including the EMSO open sea moorings.

Accessible, Interoperable and Reusable (FAIR) data principles (Wilkinson et al., 2016) and that also contributes to the IOC Ocean Best Practices System[5] (Pearlman et al., 2019).

From the SOCIB perspective, the real challenge for the next decade is the full integration of these technologies and multi-platform observing and forecasting systems. As a research infrastructure, SOCIB in partnership with CSIC and IEO scientists, combines operational, scientific and training activities. SOCIB and similar infrastructures worldwide, due to their scientific excellence, critical mass, multidisciplinary, integrated and targeted approach, open data policy and sustained funding, are establishing new research ecosystems that facilitate mission-oriented innovation. Further details are provided section SOCIB Innovation, Products and Services.

The SOCIB observing system has contributed to, the understanding of the relationship between the north-south internannual exchanges and the water masses vertical structure (Heslop et al., 2012; Barcelo-Llull et al., 2019; Juza et al., 2019), the understanding of the dynamics of meso and submesoscale eddies and their impact on the circulation (Escudier et al., 2016a) and biogeochemical fluxes (Cotroneo et al., 2016; Pascual et al., 2017; Aulicino et al., 2018) and to the sustainability of Bluefin tuna in the Mediterranean (Álvarez-Berastegui et al., 2018b). On the coastal and nearshore area, SOCIB has contributed to unravel the beach response to storminess and sediment budget dynamics in Mediterranean beaches (Morales-Márquez et al., 2018; Gómez-Pujol et al., 2019).

POSEIDON

POSEIDON[6] was established in 1997 as a research infrastructure of the Eastern Mediterranean basin for the monitoring and forecasting of the marine environment. It supports the efforts of the international and local community and addresses the requirements of science, technology and society. The general aims are (a) to establish a sustainable marine observing network in the Eastern Mediterranean, (b) to provide quality and validated forecasts of the marine environment, (c) to provide scientific knowledge and support for the study of ocean mechanisms and their variability and to address the sensitivity of marine ecosystem and biodiversity combining natural forcing factors and anthropogenic pressures, and (d) to provide a technology test bed and services to marine policy-makers and society.

The system is being developed in accordance with the policy frameworks suggested by GOOS, EuroGOOS, MonGOOS, and GEO, while maintaining a balance between the operational and research characteristics of the infrastructure through the integration of methodologies and tools developed in relevant EU initiatives and projects. The data provided by POSEIDON in the Aegean and Ionian Seas sample a wide area. The present (2018) status of the POSEIDON observatory includes multiple platforms

[5]www.oceanbestpractices.org

[6]www.poseidon.hcmr.gr

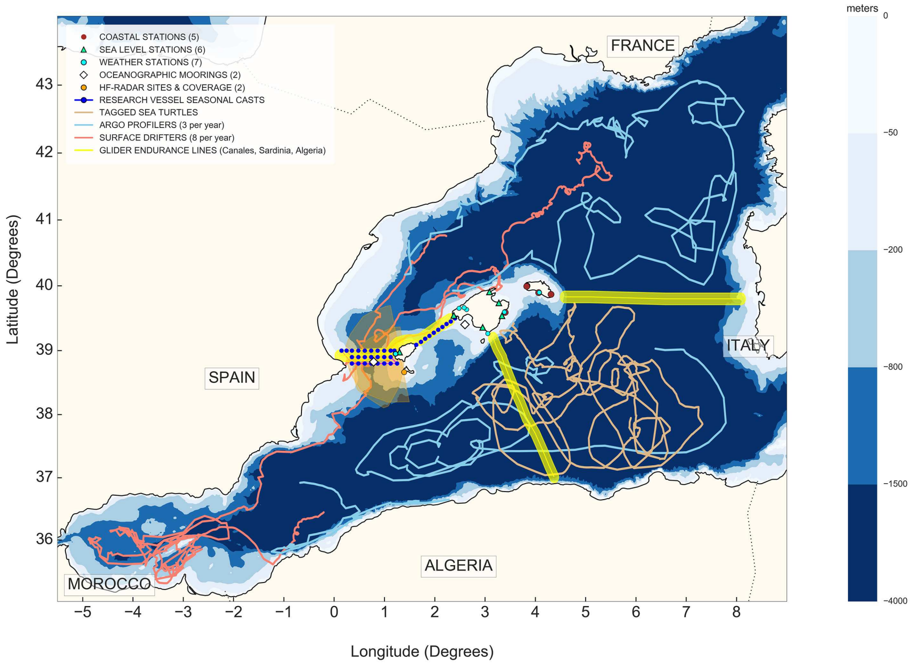

FIGURE 4 | The components of SOCIB Multiplatform Observing Infrastructures as of 2019, extending from the coast and the nearshore Balearic beaches, to the coastal and open sea, and including contributions from SOCIB to EuroArgo ERIC and Jericonext. The glider endurance line toward Sardinia is jointly operated between CNR-ISMAR and SOCIB.

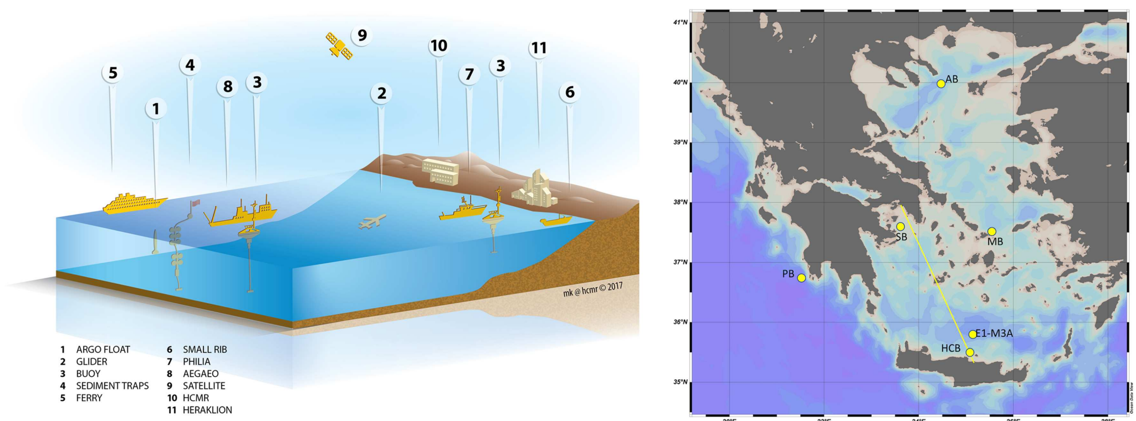

FIGURE 5 | Left: Platforms of Poseidon observatory. Right: Map showing the location of the POSEIDON system fixed platforms (AB, Athos Buoy; MB, Mykonos Buoy; PB, Pylos Buoy; SB, Saronikos Buoy; E1-M3A Buoy) and Ferrybox route (yellow line) [from Petihakis et al. (2018)].

(**Figure 5**) operating at various spatiotemporal scales (**Figure 6**). The components are:

- Three wavescan buoys are deployed in the S. Aegean (E1-M3A), N. Aegean (ATHOS) and Ionian waters (PYLOS) provide meteorological, physical and biochemical (O_2, Chl-a) data (Petihakis et al., 2018).
- A Ferrybox system (FB) operating on the route connecting the ports of Piraeus (Athens) and Heraklion. This fully automated, flow-through system includes sensors of temperature, salinity, fluorescence, turbidity and pH. FB has been proven to be a helpful tool in the study of water circulation (e.g., modified Black Sea Water flowing in the Aegean Sea), in particular when assimilated into prognostic numerical circulation models to improve their accuracy (Korres et al., 2014).
- Sampling of seawater and plankton, which is regularly conducted next to the fixed biochemical platforms and on board the FB. R/V visits are made monthly next to the E1-M3A site and the HCB.
- The Greek Argo infrastructure (www.greekargo.gr), which had 15 deployed floats in 2015 and 2016 (five of which were BGC-Argo) and aims for a total of 25 Argo floats, further contributes

to the international Argo community efforts to monitor the Eastern Mediterranean region.

- Interaction with several land-based facilities located nearby the observatory, which is necessary for sensor maintenance and the analysis of discrete samples. The calibration lab, micro- and mesocosms, meteorological stations, and atmospheric deposition station are also key land-based components. In particular, the calibration lab, considering the local environmental conditions, is a powerful tool for the calibration of sensors deployed in the wider Mediterranean Sea (Bozzano et al., 2013; Pensieri et al., 2016).

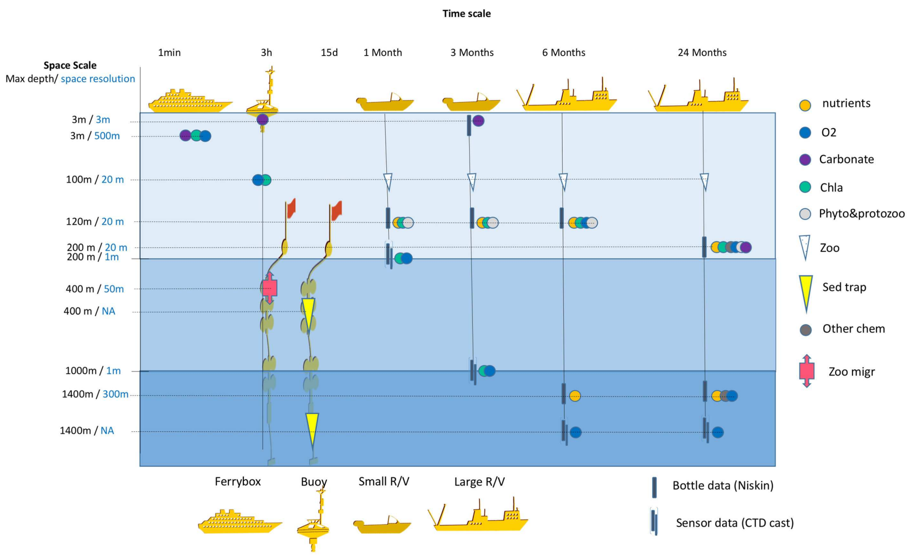

FIGURE 6 | Time and space resolution of data acquisition by the different platforms of the POSEIDON observatory (Argos, Gliders excluded). Space resolution is vertical except for Ferrybox. Carbonate: pH or CT&AT, Other chem: other chemical parameters, Sed trap: sediment trap, Phyto & protozoo: phytoplankton and protozoans; Zoo: metazoans, Zoo migr: ADCP backscatter data for zooplankton-micronekton migration [from Petihakis et al. (2018)].

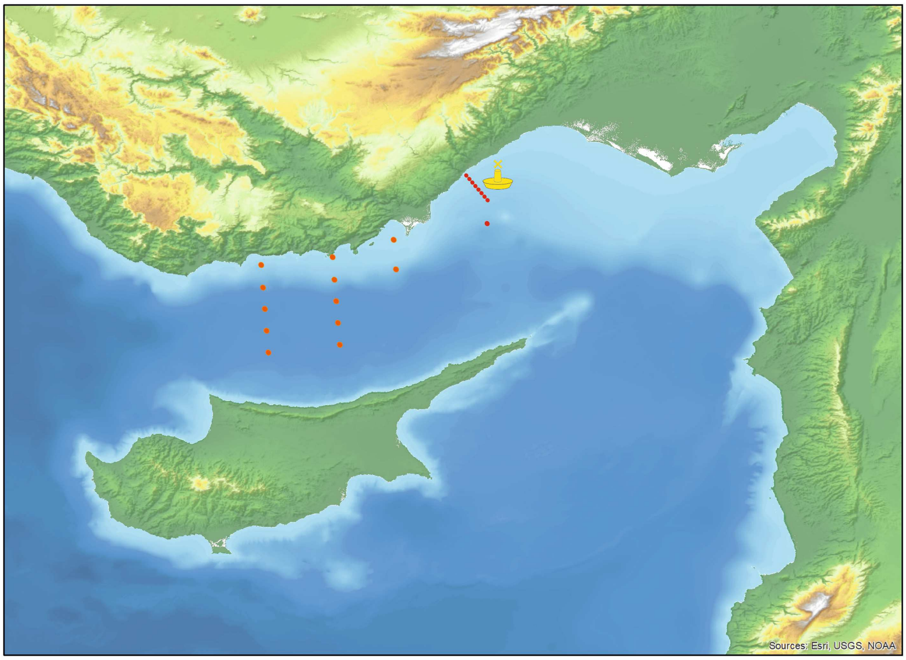

FIGURE 7 | DEKOSIM Erdemli Time Series stations shown in red, the mooring site and seasonal monitoring indicated with orange.

The critical issue for the POSEIDON observatory is its sustainability. The multiparameter, multiplatform observatory approach allows for the participation in various research projects and thus the provision of funds through multiple sources. In addition, the long experience acquired, and the particular conditions of the Eastern Mediterranean, makes the observatory an excellent test bed for new technology.

The POSEIDON system will offer additional products to a wider range of society users, through its expanded NRT data delivery, proxy estimations, hazard mapping, warning systems and higher resolution, in addition to addressing specific scientific questions. For example, deep water ADCP data from the Cretan Sea provided insights into important processes in terms of ecosystem functioning, such as zooplankton migration (Potiris et al., 2018). The observation of the various patterns of vertical migration and of mesopelagic inhabitants, makes possible the investigation of the role of these components in organic carbon sequestration.

DEKOSIM

The Center for Marine Ecosystems and Climate Research (DEKOSIM) is the leading oceanographic research center in Turkey. The center builds upon four decades of experience from the Middle East Technical University's Institute of Marine Sciences. DEKOSIM provides knowledge transfer tools to assist authorities and other stakeholders to manage routine tasks and evaluate trends.

DEKOSIM activities since 2012 can be grouped into the three sectors of observing systems, model products and policy outputs. Observing activities comprise fixed and mobile observatory development and expedition-based time series high-frequency observations. To initiate a sustainable, more comprehensive and long-term monitoring programme in the north-eastern Mediterranean, DEKOSIM started the Erdemli Time Series (ETS) programme in 2013, which built on the fragmented, semi-regular time series measurements collected since 1997. In ETS, a total of 9 stations between 20 and 500 m depths are monitored monthly for T, S, and DO (**Figure 7**). Further, monthly measurements for biological and chemical essential ocean variables (T, S, DO, Chl, Tur, Par, Secchi disk) are conducted at 4 selected stations at 20, 100, 200, and 500 m depths. In addition, monthly trawl surveys have been carried out since 2007 to investigate and monitor demersal fish stocks. A mooring system that has 7 underwater inductive sensors (T, S, DO) at different levels of the water column and meteorological sensors was deployed on the ETS at 100 m water depth. The data can be acquired daily from the mooring. DEKOSIM also supported Argo deployments in the region and 850 profile data have been acquired from 4 Argo floats in Black Sea and 2 in Mediterranean since 2013 within the DEKOSIM. The DEKOSIM information system provides data storage and quality control facilities, according to Seadatanet procedures. The two major scientific achievements, deriving from the DEKOSIM monitoring, are related to the characterization of a possible formation pathway for the LIW in the northern Cilician Basin and the strong land-sea coupling

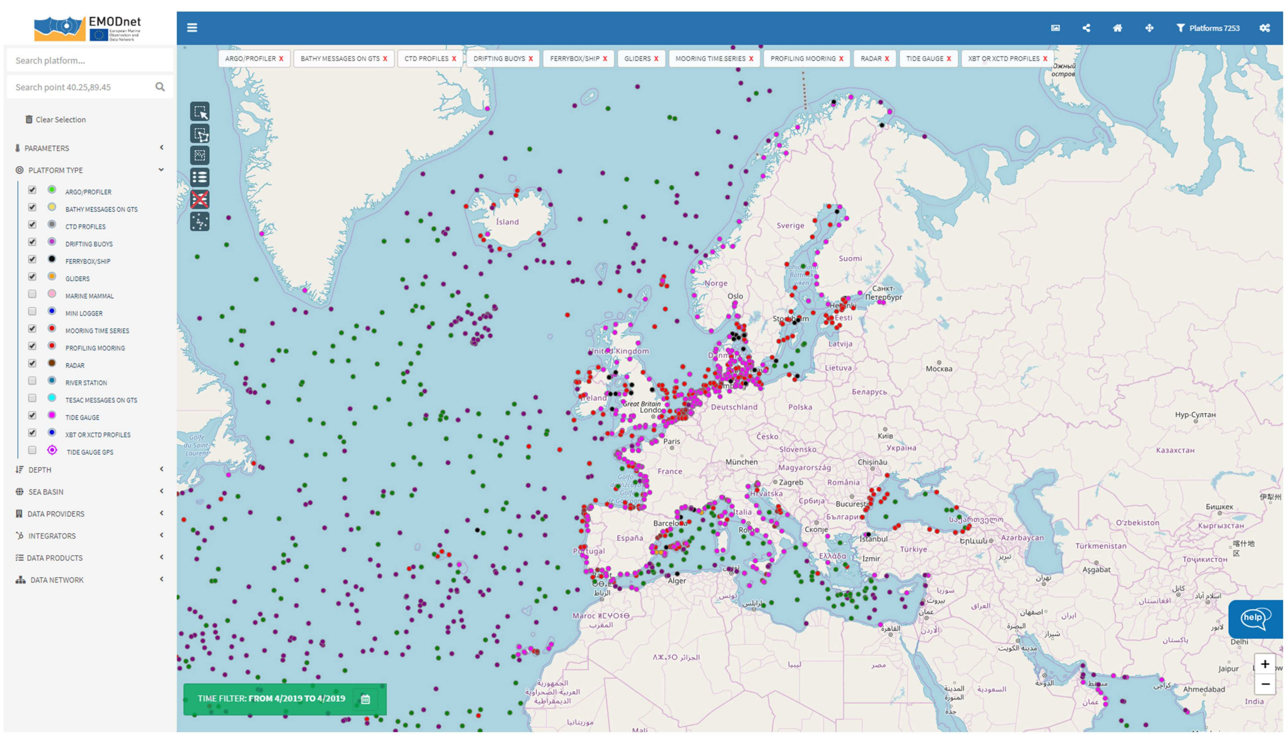

FIGURE 8 | Snapshot of the sampling platforms sending real time data to EMODnet Physics Portal (http://www.emodnet-physics.eu/Map/) as of 1 week in April 2019.

observed in North-eastern Mediterranean and the resultant relatively high productivity.

SELIPS-ISRAMAR

The South Eastern Levantine Israeli Prediction System (SELIPS) and the Israel Marine Data Center (ISRAMAR, https://isramar.ocean.org.il) were established 20 years ago at the Israel Oceanographic & Limnological Research (IOLR) Center as a research and monitoring infrastructure. They provide scientific data and knowledge and effective management and protection programmes for the marine environment. Both systems were integrated in several national and international/EU initiatives dedicated to operational oceanography and data archiving.

The SELIPS-ISRAMAR contain various forecasting and observational platforms operating at different scales. Since 2002 bi-annual monitoring cruises have been conducted in the SE Levantine basin along transects from 20 to 1,700 m water depths, and 70 km offshore by the R/V Shikmona until 2016 and further by the R/V Bat Galim. Profiles of pressure, temperature, salinity, dissolved oxygen and fluorescence, along with water samples for alkalinity, dissolved oxygen, nutrients, chlorophyll-a (Chl-a), picophytoplankton and bacterial abundances, primary and bacterial production and bacterial diversity are collected at eight permanent stations.

IOLR established a modern near real-time meteo-marine monitoring station in 1992, 2.3 km offshore at the Hadera coal terminal (central Israel), which is identified as GLOSS station #80 (https://isramar.ocean.org.il/isramar2009/Hadera/). The parameters monitored are sea level, waves, seawater temperature, salinity, dissolved oxygen, turbidity, fluorescence, and atmospheric pressure. A similar monitoring station was established 2.3 km offshore of Ashqelon (south Israel) in 2012.

IOLR has operated the Deep Levantine Marine Station (DeepLev) since November 2016, which is the first deep-moored research and monitoring station in the SE Levantine Basin (LB), located 50 km offshore of Haifa (Israel) at a water depth of 1,500 m. It carries an array of instruments, including various current meters (ADCPs), CTDs, sediment traps, fluorometers and turbidity sensors, aiming to produce a long-term, high-resolution characteristic of the physical, chemical, and biological dynamics of the water column. In addition, IOLR operates ocean gliders for monitoring activities, which conduct bi-annual transects along N-S and E-W at the SE LB.

Finally, since 2001 ISRAMAR has been a repository for oceanographic data (physical, chemical, biological) and acquires, archives and distributes data and information about the marine environment. It also contain a marine barcoding database consisting of DNA-barcode tagging, identification and taxonomy with the purpose of promoting taxonomic knowledge for marine biodiversity (https://isramar.ocean.org.il/IsraelBarcoding). Since 2007, a synoptic database of ocean color parameters offshore of Israel using Earth Observation has been generated by SISCAL (Satellite-based Information System on Coastal Areas and Lakes, operated by IOLR). These include maps of the Sea Surface Temperature (SST), Chlorophyll-a concentration, Total Suspended Matter and Secchi depth, obtained from operational ocean observing satellites.

The SELIPS-ISRAMAR has acquired 30 years' worth of hydrographic observations, showing that the south-eastern Mediterranean Sea is getting saltier and warmer at rates in agreement or higher than the IPCC 2014 high end prediction (Ozer et al., 2017). In addition, Lagrangian analysis of circulation patterns has provided a better understanding of shelf-deep sea interactions and filament formation (Efrati et al., 2013).

PORTUS (Puertos del Estado System)

The observational component of the Portus system in the Mediterranean Sea consists of 7 deep water buoys (able to measure currents, SST, salinity, wind, atmospheric pressure, air temperature and waves), 6 coastal buoys (waves and SST), 2 HF radar systems (Catalan coast and straits of Gibraltar) and 16 tide gauges. This comprehensive observing system is fully integrated into the modeling component of the Portus (see the section below) and serves data for multiple socio-economic sectors with the main customer being the Spanish Port system, via the SAMOA service (see section Downstream Services in Response to Societal Challenges and Stakeholders). Real-time data access is provided via Portus web site[7].

MAOS (Mobile Autonomous Oceanographic Systems)

The MAOS[8] is an Italian infrastructure using mobile autonomous instruments, such as gliders, floats and drifters, to measure marine properties with its main focus on the Mediterranean Sea. It contributes substantially to the Argo fleet in the Mediterranean with the deployment of about 20 floats annually since 2012. In addition to standard Argo floats, MAOS has operated several floats equipped with biogeochemical sensors and the first floats profiling as deep as 4,000 m in the Mediterranean. MAOS is also coordinating the deployment of all the Argo floats in the Mediterranean and is responsible for the delayed mode quality control of their data, in the framework of MedArgo (Poulain et al., 2007), the Argo Regional Center for the Mediterranean. Among various applications, Argo float data have been used to study convection and dense water formation in the Adriatic Sea (see for instance Bensi et al., 2013).

MAOS also regularly operates several types of surface drifters to monitor the surface currents and temperature, and maintains a historical drifter database (Menna et al., 2018). It uses four gliders to measure water mass properties in the Mediterranean, with the main focus on the Italian seas and the Levantine Basin. MAOS also runs a glider endurance line across the southern Adriatic Sea to monitor dense water formation processes.

RITMARE

The Italian RITMARE Flagship Programme, which began in 2012, aimed to implement the RITMARE Ocean Observing System for the Italian seas by building on existing infrastructures, to help implement national and European environmental regulations and to contribute to the future European Ocean Observing System. The network now integrates different platforms, i.e., coastal buoys, oceanographic towers, coastal, open ocean and cabled moorings, HF and X-band radars, gliders,

[7]http://portus.puertos.es
[8]http://maos.inogs.it

satellite products and modeling components. The ongoing efforts are aimed at increasing the number of active platforms, to align the sensors, improve the near real time QA/QC, and to develop new remote sensing algorithms and products.

The system presently consists of 17 fixed point observatories, 5 gliders, a variable number of operating drifters and floats, 3 HF radars, and several operational models. In addition, repeated transects on board R/Vs are conducted in all Italian Seas. Since 2015 a 6-monthly glider transect has been conducted between Sardinia and the Balearic Islands, in cooperation with SOCIB (see **Figure 4**).

The different components of the sustained RITMARE Observing System allow for the description of the carbonate system in coastal and offshore areas (Cantoni et al., 2012, 2016), and the climatology and long term trends of wind waves (Pomaro et al., 2017), to gain insights into dense water formation and dense shelf water cascading processes (Langone et al., 2016; Schroeder et al., 2016), and to detect how climate change induces rapid responses in a marginal sea such as the Mediterranean (Schroeder et al., 2017).

IEOOS

The Spanish institute of Oceanography (IEO) maintains a historical ocean observing system around the Iberian Peninsula, and the Canary and the Balearic Islands, known as IEOOS (Tel et al., 2016). This system provides quality-controlled data from a wide network of tide gauges, hydrographic monitoring sections, permanent moorings, and underway monitoring and is a key contribution the ARGO international programme. Data and metadata following international standards are incorporated into the IEO data archive, linked to the Sea-DataNet network, and thus made accessible.

The RADMED monitoring programme (Lopez-Jurado et al., 2015) is a key element of IEOOS, and has systematically collected hydrographic sections from Barcelona to the Alborán Sea and around the Balearic Islands for over 20 years. This sustained effort has enabled the characterization of the seasonal and interannual variability, the effects of winter convective processes, the presence of water masses, mesoscale structures, transport and exchange between basins, cycles, trends and possible climate changes to be established, in addition to environmental and ecological studies of species (Balbin et al., 2014; García-Martínez et al., 2018). RADMED data have been also used to update temperature and salinity mean values and trends in the Western Mediterranean (Vargas-Yañez et al., 2017). Additionally, the data has been used to characterize spatial and temporal long-term patterns of phyto and zooplankton in the Western Mediterranean (García-Martínez et al., 2019).

Forecasting Systems

The present European leadership in operational oceanography and ocean forecasting has its origin in the coordinated efforts in the Mediterranean that started in the early 1990s, due to EuroGOOS (Pinardi and Flemming, 1998) and the associated EU funded projects (Pinardi and Coppini, 2010), which are the origin of the present CMEMS Med-MFC discussed below.

CMEMS

The CMEMS systems in the Mediterranean are strongly connected to MONGOOS. The Mediterranean Monitoring and Forecasting Center (Med-MFC) is one of the regional production centers of CMEMS. Med-MFC operatively manages a suite of numerical model systems that provide analyses and forecasts of physical and biogeochemical variables for the Mediterranean Sea, with a horizontal resolution of 1/24° (about 3.5 km). The physical component of Med-MFC is provided by a coupled hydrodynamic-wave modeling system (Clementi et al., 2017), assimilating temperature and salinity vertical profiles, and satellite Sea Level Anomaly (Dobricic and Pinardi, 2008). It operationally provides daily updates of 10-day forecasts and weekly updates of analyses. Products include: 3D Temperature, Salinity, Currents; 2D Sea Surface Height, Mixed Layer Depth, Bottom Temperature, Stokes Drift, and Wavenumber.

The biogeochemical component of Med-MFC is forced by outputs provided by the physical component and assimilates the surface chlorophyll concentration measured from satellites. Products include 3D daily fields of Chlorophyll, Nitrate (NO_3), Phosphate (PO_4), Net Primary Production, Phytoplankton Biomass, Dissolved Oxygen, CO_2 partial pressure, and Seawater Acidity (pH).

The wave component of Med MFC is based on a high resolution (1/24°) operational wave forecasting system that provides on a daily basis 1-day hourly hindcasts and 5-days hourly forecasts of the wave environment in the Mediterranean Sea. The 17 available wave products include significant wave height, wind and primary/secondary swell significant wave height, periods, direction, and Stokes Drift velocity.

The CMEMS products support major scientific research and applications, including the evaluation of the sea level trend dynamics (Pinardi et al., 2014), the overturning circulation in the Mediterranean Sea (Verri et al., 2017; Pinardi et al., 2019), oil spill hazard mapping (Liubartseva et al., 2015) and an oil spill emergency response decision support system (Zodiatis et al., 2016a). Multi-year products (both reanalysis and hindcasts) at daily/monthly frequency are also regularly updated once per year and they cover by now the past 30 years. All operational products are made available through the CMEMS service delivery system[9].

SOCIB

The Modeling and Forecasting Facility at SOCIB has successfully developed and implemented three prediction systems which are now run and evaluated on an operational daily basis. These are: the operational regional circulation model nested to CMEMS Med-MFC (Juza et al., 2016; Mourre et al., 2018), the meteo-tsunami pre-operational forecasting system for Ciutadella harbor (Renault et al., 2011; Licer et al., 2017) and the wave forecasting around the Balearic Islands. Research is also conducted to continuously improve and extend the capacity of these systems. The most significant recent advances include a new characterization of the dynamics of ocean eddies in the Algerian basin (Escudier et al., 2016a) and the analysis of multi-year high-resolution numerical simulations to investigate fish

[9]http://marine.copernicus.eu/services-portfolio/access-to-products/

larvae dispersion (Calò et al., 2018) or simulate high-resolution observations potentially obtained from future satellites such as SWOT (Gómez-Navarro et al., 2018) and the application of machine learning techniques for the interpolation of simulated observations of satellite altimetry (Fablet et al., 2018).

Significant advances have been also achieved on the understanding and simulation of physical-biogeochemical processes, for example on the combined effects of the Atlantic Water inflow at Gibraltar and the associated eastward jet and winds over the phytoplankton distribution in the Alborán Sea (Oguz et al., 2016, 2017), and on the integration of multiplatform observations and high-resolution modeling through data assimilation (Pascual et al., 2017; Hernandez-Lasheras and Mourre, 2018). These results have implications in terms of operational response to emergencies, sustainable management of the marine environment and ecosystems health, and climate.

POSEIDON

Forecasting tools are centrally placed in the POSEIDON system, with a number of state-of-the-art weather, wind waves, ocean circulation and marine ecosystem numerical models, initialization and data assimilation schemes providing 5-days ahead information on daily basis regarding the atmospheric (Papadopoulos et al., 2002), sea state (Korres et al., 2011), and hydrodynamic conditions (Korres et al., 2010) in the Aegean/Ionian Seas and in the Mediterranean, in addition to the ecosystem functioning of the whole basin. In terms of general calibration, validation activities are applied to the operational models as data from the observatory are used in conjunction with experiments (e.g., mesocosms) for the analysis and modeling of specific processes (e.g. Tsiaras et al., 2017) and assimilation algorithms of sea color data are tested and validated in biogeochemical models (Kalaroni et al., 2016).

CYCOFOS

The Cyprus coastal ocean forecasting system, known as CYCOFOS, has been providing operational hydrodynamics and sea state forecasts in the Eastern Mediterranean since early 2002. Recently, it has been improved with the implementation of a new hydrodynamic, wave and atmospheric modeling system with the objective of targeting larger and higher resolution domains, at regional and sub-regional scales (Zodiatis et al., 2016b). For the new CYCOFOS hydrodynamic modeling systems a novel parallel version of the Princeton Ocean Model has been developed and implemented with a 2 km resolution over the entire Eastern Mediterranean and in the Levantine Basin with a resolution of ∼600 m. Both models are nested in the CMEMS Med-MFC. The Weather Research and Forecasting atmospheric model (WRF) has been implemented in the same domain as the SKIRON atmospheric system[10] (Kallos et al., 1997; Papadopoulos et al., 2002), to provide the backup forcing for the CYCOFOS new modeling systems.

All the CYCOFOS modeling systems received an extended cal/val against Argo profiles, satellite SST time series, *in-situ* wave time series and METAR observations (Zodiatis et al., 2018). The CYCOFOS modeling system provides a higher-resolution quality-controlled forecasting data fit for the needs of end users in the fields of maritime safety and oil spill predictions, particularly in view of the recent exploration and exploitation of the hydrocarbons in the Eastern Mediterranean Levantine Basin. Over the past 10 years, the majority of *in-situ* observations around Cyprus have been collected from two ocean gliders, which have been shown to improve the operational forecasting skill of CYCOFOS at scales from 10 to 50 km, most notably in the region of the Cyprus Eddy (Hayes et al., 2019).

SANIFS

The southern Adriatic Sea and Northern Ionian Forecasting System (SANIFS, Federico et al., 2017) is an unstructured grid limited area forecasting system downscaling the CMEMS Med-MFC forecasts up to 10 m along the coasts and inside the harbors. SANIFS is based on a 3D finite element hydrodynamics model (Umgiesser et al., 2004) and it considers 91 vertical levels with a 2 m resolution to a 20 m depth, progressively decreasing the resolution near the bottom. Tidal forcing is applied to the lateral boundaries of the model so that the forecasts can be used for several coastal applications such as coastal erosion, inundation forecasts, and marine pollutants dispersal hazard mapping. The model is nested to CMEMS and forced with ECMWF products with a 6 h frequency and a ∼12 km horizontal resolution. The results are available at the SANIFS site[11].

PORTUS

The Portus forecasting component operates both at the regional scale, with sea level and wave forecasts covering the whole Mediterranean basin, and at the port and coastal scale, with forecasts of circulation (nested into CMEMS models) and waves. At the regional scale, the sea level forecast is provided by a 2D barotropic model covering the whole basin, which has been recently complemented by a multi-model Bayesian model average ensemble based on Copernicus forecasts. The wave forecast is based on the using of WAM forced with Spanish Met Office winds. At the coastal and port scale, multiple models are used to provide high resolution services for ports and coastal areas (see description of SAMOA at section Puertos del Estado Downstream Services).

CAPEMALTA

CapeMalta is the ocean forecasting system for the Maltese Islands. The ROSARIO Malta Shelf forecasting system[12] provides routine online thermo-hydrodynamic predictions for the extended area around the Maltese Islands up to the southern Sicilian coast. The system operates through the use of an eddy-resolving numerical model with two distinct spatial resolutions of 1/64o and 1/96o (about 1 Km) with 1-h and 3-h averaged color maps and animations of temperature, salinity and velocity fields at the sea surface and at selected depths, and a forecast horizon of 4 days. The MARIA Malta Atmospheric and Wave forecasting systems consist of an operational chain of meteo-marine models with downscaling to high resolution sub-domains for the region

[10] http://forecast.uoa.gr

[11] http://sanifs.cmcc.it/

[12] http://www.capemalta.net/MFSTEP/results.html

north of 34° latitude in the Sicilian Channel and comprising the Maltese Islands.

The wave forecast uses the 3rd generation WAM Cycle 4 spectral wave model. The model is forced by surface wind and runs daily to produce a 72-h forecast on a high-resolution grid (1/8°) over the Central Mediterranean. More refined wave conditions in the coastal and near-shore areas are predicted at high spatial resolution by using the SWAN model over the domain defined by 14.040–14.700° longitude and 35.665–36.206° latitude, and a spatial resolution of 0.002°, generating output fields every 3 h.

Data Assembly Systems

CMEMS Thematic Assembly Centers

The CMEMS data assembly structure is organized around *in-situ* and satellite Thematic Assembly Centers.

The CMEMS *in situ* Thematic Assembly Center (*in situ* TAC) (Petit de la Villeon et al., 2018; Le Traon et al., 2019) integrates near real-time *in-situ* observational data. These data are collected from the European members and complemented by the observations collected through the GTS in the area. The details of the physical parameters and data management procedures can be found in Copernicus Marine *in situ* TAC Data Management Team (2018). The data are quality controlled using automated procedures and the database is updated continuously, providing observations within 24–48 h from acquisition. CMEMS Mediterranean *in-situ* TAC works in coordination with MONGOOS (section MONGOOS Collaborative Framework) and EMODnet to access almost all the real-time data collected in the basin by the European Members States.

The CMEMS remote-satellites Thematic Assembly Centers (Sea Ice TAC, Surface Wind TAC, Sea Level TAC, Ocean Color TAC, Sea Surface Temperature TAC, Wave TAC, Multi Observations TAC) make available several data products from all functioning satellites for altimetry, infrared and visible multi-band radiometers every day. The satellite data are also re-processed every week giving the optimal estimates of the atmospherically corrected sea level.

EMODnet

EMODnet is a data assembly initiative supported by the European Directorate General MARE, which collects, transforms and makes available in a consistent manner several thematic data sets related to the marine environment. These are bathymetry, geology, seabed habitats, chemistry, biology, physics, and human activities. They span a larger set of EOVs, which are required in the fulfillment of the UN SDGs. They are complementary to the CMEMS *in situ* TAC because they are mainly concerned with historical data and making accessible the past and present data in a common, interoperable format. EMODnet has had, from the beginning, a wider scope of application than CMEMS, thus making data available for reuse to the overall European and International community. EMODnet relies strongly on *in-situ* TAC data collection.

The EMODnet Physics Web GIS system allows the monitoring of the working platforms in the Mediterranean Sea on the basis of different time intervals and thus it is a very useful tool for planning new deployments of measuring platforms (see **Figure 8**).

The Mediterranean Sea is an area of EMODnet intensive data assembly in all thematic areas, and the EMODnet Checkpoint initiative has assessed the data adequacy of the basin scale monitoring system[13].

SeaDataCloud

SeaDataCloud[14] is a European-wide infrastructure for the development of standardized access to European marine data from more than 100 data centers. Its aim is to preserve and make re-useable marine observations ranging from ocean physics to chemistry and biology. It uses the strategy and standards of the Unesco IODE programme.

The work of SeaDataCloud is the basis of the EMODnet Portals, and develops data management standards, vocabulary, and quality control procedures, and encourages best practices throughout the marine data management sector. SeaDataCloud is the most recent outcome of 15 years' continuous development, and it will use cloud and high-performance computing technology for better performance. SeaDatacloud in the Mediterranean connects the National Oceanographic Data Centers (NODC) and produces high quality climatologies using historical data from 1900 to the present.

Regional Data Management Systems

The Mediterranean observing systems described in section Multi-Platform Observing Systems all have dedicated data management infrastructures. Here we only present three of the main and permanent systems in the Eastern and the Western Mediterranean. MOOSE relies on the national data management centers for real-time and delayed-mode data (SEDOO, SISMER). Data sets are organized by platform and DOIs are attributed to each platform deployment. Delayed mode quality controls are carried out by MOOSE while real-time data are quality controlled by standard procedures at Coriolis. These data centers allow for the dissemination of the data to the public in internally approved formats. The POSEIDON Data Center, as the regional data collection unit of the CMEMS, ensures that the recorded data is compatible with other large European data infrastructures (EMODnet, CMEMS and SeaDataNet). Data can be visualized through the POSEIDON website (fixed platforms, Ferrybox) and the MONGOOS data portal[15], while the data are freely available to the public, the stakeholders and the scientific community. The SOCIB Data Center also manages the full data life cycle: acquisition, assembly and processing (including quality control), archiving, preservation and dissemination. A variety of systems have been developed to achieve these goals. For example: a glider toolbox (Troupin et al., 2016) for data processing and assembly is available through GitHub and is being used for processing glider data internationally. A new Data Catalog API (Fernández et al., 2018) allows discovering the SOCIB data catalog and retrieving

[13]http://www.emodnet-mediterranean.eu/

[14]https://www.seadatanet.org/

[15]http://www.mongoos.eu/data-center, all platforms except sediment traps and ADCP.

its data directly. DOIs are also attributed by platforms and/or for dedicated intensive experiments (Cotroneo et al., 2019).

MONGOOS COLLABORATIVE FRAMEWORK

The Mediterranean Sea basic systems/services were first implemented by EuroGOOS in the late 1990s (Pinardi and Flemming, 1998; Pinardi and Woods, 2002). More recently the GOOS Regional Alliance (GRA) for the Mediterranean Sea was established as the Mediterranean Operational Network for the Global Ocean Observing System (MONGOOS), which also serves also as a ROOS for EuroGOOS. MONGOOS was established in 2012, merging the previous two groups, MOON and MedGOOS, to further develop operational oceanography in the Mediterranean Sea.

MONGOOS has identified the relevant regional stakeholders and reference users of the MONGOOS basic services and products, and memorandums of agreements have been established with them to formalize the work. They are available from the documents section of the MONGOOS web site[16].

MONGOOS Coordinated Observational Capacities

A catalog of MONGOOS monitoring platforms is offered via the MONGOOS Data Center, integrated into the MONGOOS web page. Access to real time data from most of the MONGOOS monitoring platforms is provided through the CMEMS *in-situ* TAC and the EMODnet Physics Portal. Although there are evident gaps (e.g., no tide gauges are reported in Greece), it constitutes one of the most comprehensive catalogs of available oceanographic measurements in the region. **Figure 9** shows the distribution of wave, sea level, SST, and salinity measuring platforms.

There are 58 buoys capable of measuring waves, most of which are directional (**Figure 9A**). Coverage is more complete in the Western basin, and there is an almost total absence along the African coast, with the exception of Ceuta and Melilla stations. A total of 100 sea level stations are reported (**Figure 9B**). There is a significant gap in Eastern Europe, due to lack of coordination with the community. A total of 37 current meters are operational across the region (**Figure 9C**). Water temperature is the most frequently and regularly measured variable, with 113 stations (**Figure 9D**). Fifty salinity stations are reported.

Several buoys and towers can measure atmospheric variables over the sea and the catalog contains information of 80 Meteorological stations capable of measuring air pressure, temperature and wind. A total of 11 HF radar systems (with an overall of 32 HF radial sites), accounting for 52% of the European HFR network (Rubio et al., 2017), have been or are currently in operation in the area (**Figure 10A**). More information can be found at http://www.mongoos.eu/hf-radars. Additionally, HF radar datasets can also be found in the new product (INSITU_GLO_UV_NRT_OBSERVATIONS_013_048)

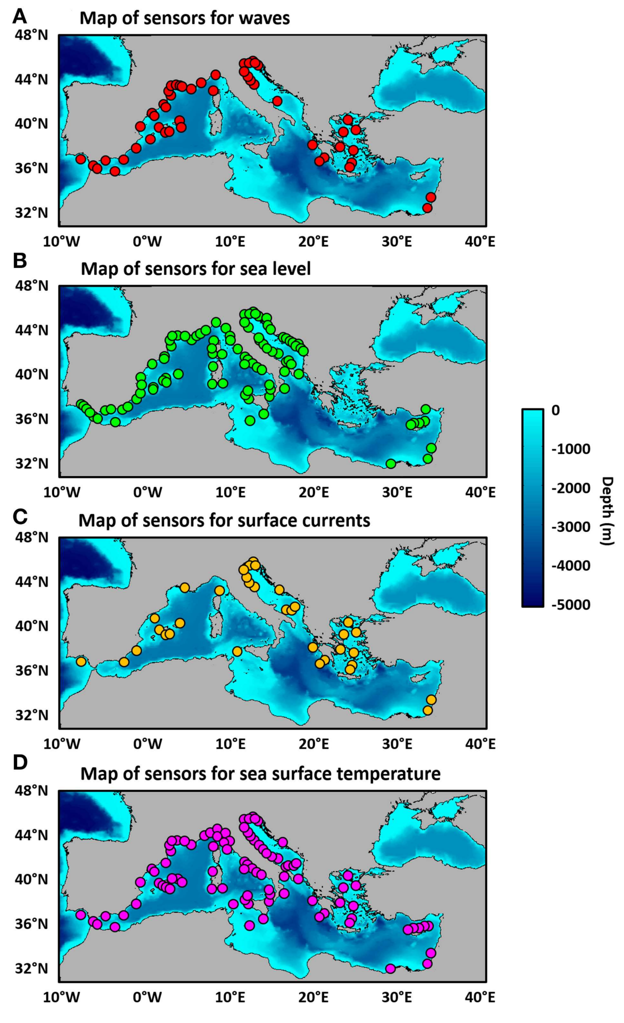

FIGURE 9 | Map of sensors deployed in the Mediterranean Sea for monitoring purposes (as in 2017): **(A)** waves, **(B)** sea level, **(C)** surface currents, and **(D)** sea surface temperature.

for near real-time surface current data in the CMEMS Catalog (V5), included in the recently updated CMEMS service release.

Since the early 2010s over 60 Argo floats have been established in the Mediterranean basin, with 78 instruments in June 2019 (**Figure 10B**) and 7 Glider facilities (**Figure 10C**). More information can be found at the Mongoos web site[17].

In summary, for some variables and in certain regions, the monitoring system is satisfactory. For example, the number of tide gauges on the western European Mediterranean coast is sufficient for most of the applications (study of sea level trends, storm surge monitoring, etc.). Similar situations can be found for wave buoys. Nevertheless, the gaps and limitations of the monitoring system are clear and often significant. First, there is a marked North-South imbalance, with the southern shores not coordinated with the northern basin monitoring system.

[16]http://www.mongoos.eu/

[17]http://www.mongoos.eu/profilers-and-drifters-med-argo

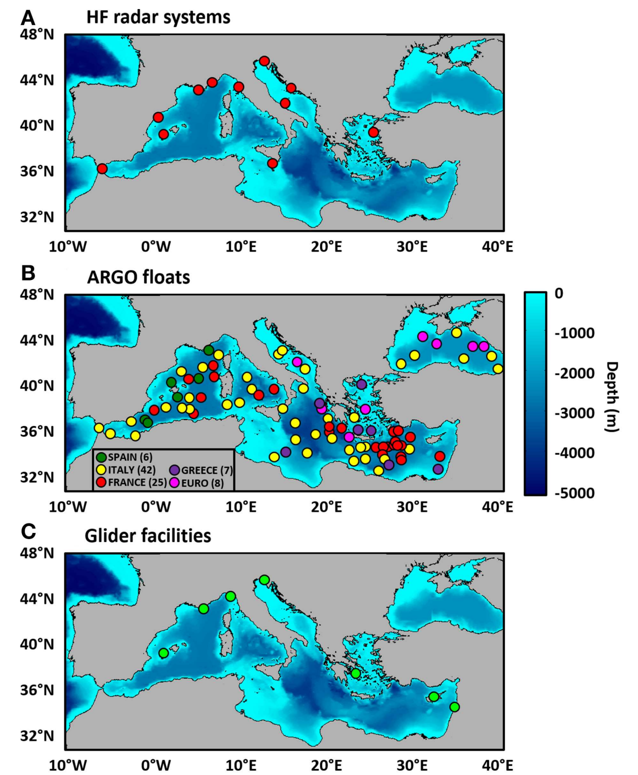

FIGURE 10 | Map of sensors deployed in the Mediterranean Sea for monitoring purposes: **(A)** High Frequency radars, **(B)** Argo Floats as in 2018, and **(C)** Gliders.

Even on the European coasts, there is an obvious unequal distribution of sensors due to the lack of global planning. Other variables like currents are clearly under-sampled throughout the region, and the same applies for salinity and water temperature, although for these variables data from gliders and Argo serve to mitigate the situation. In any case, due to the size of the relevant dynamical and mesoscale structures in the region, the limited number of platforms is insufficient to properly contribute to data assimilation in numerical models.

MONGOOS Coordinated Forecasting Systems

A catalog of regional to subregional modeling and forecasting systems outside CMEMS is provided through the MONGOOS showcase tool. The tool directly links to the services operated by institutions across the Mediterranean Sea. From the analysis of the data available on the tool, the following description of the modeling situation in the region is obtained.

There are 33 recorded, operational wave models in the Mediterranean Sea. Some of them cover the whole basin and others are nested in the CMEMS wave model or others, to provide solutions to harbors or coastal areas. Most of the large-scale implementations are based on the WAM and Wave Watch models, while the coastal applications use mostly SWAM. The atmospheric forcing used by the wave models also differs, including ECMWF, HIRLAM, COSMO and WRF atmospheric limited area forecasting models. The Eastern and Western sub-basins have a similar number of models and there is an absence of high-resolution nested application on the African Coast.

In terms of circulation and hydrography, most of the models are nested into the CMEMS Med-MFC. Nested forecasting systems use several types of models, including the Princeton Ocean Model (Blumberg and Mellor, 1987), ROMS (Regional Ocean Modeling System, Shchepetkin and McWilliams, 2005), NEMO (Nucleus European Model of the Ocean, Madec, 2016) and SHYFEM (Ferrarin et al., 2019). These limited area models usually do not assimilate observations, which are instead assimilated in the CMEMS model.

There is good coverage in both sub-basins, with a typical forecasting horizon of between 5 to 10 days. The common resolution is 1 or 2 km, but is as low as 200 m in the case of the PORTUS model at the Strait of Gibraltar and SANIFS, where resolutions of 10 m are attained inside the harbors. The number of vertical levels is typically between 20 and 100 using various coordinate systems. Almost all the operational sub-regional models are executed once per day.

Some of the models use atmospheric pressure forcing, which is fundamental for sea level (storm surge) short-term forecasts. A few systems specialize in this variable and phenomenon, working in 2D barotropic mode. In this category it is worth to mention Kassandra system (Ferrarin et al., 2013) and the Nivmar service (Alvarez Fanjul et al., 2001), part of the PORTUS system.

In terms of quality and quantity of the operational systems, the Mediterranean area is reasonably well-covered, but few comparison exercises to understand the gaps and performance limitations are conducted and should be increased in the future. Also, by taking advantage of the many models present, ensemble multi-model forecasting in some coastal areas could be evaluated.

DOWNSTREAM SERVICES IN RESPONSE TO SOCIETAL CHALLENGES AND STAKEHOLDERS

In this section we present some of the most relevant and most used downstream services developed in response to societal challenges and stakeholders. Operational oceanography currently reaches thousands of users through services addressing societal challenges (e.g., CMEMS), including maritime safety, coastal and marine environment management, climate change assessment, and marine resources management. Freely available products from CMEMS allow the development of specific applications, such as Decision Support Systems (DSS) and services for users and stakeholders.

Oceanographic products from CMEMS and downscaled sub-regional and national products are used, transformed, and provided to users, private companies and stakeholders through adding-value chains (downstreaming), which consider the development of specific solutions, advanced visualization, the use of multi-channel technological platforms and specific models and algorithms.

Several examples of downstream services are given below.

Puertos del Estado Downstream Services

Approximately 85% of total imports and 60% of Spanish exports are channeled through ports, illustrating the vital role they play in the national economy. The ports suffer from the extreme events of the essential physical variables, and particularly wind, waves and sea level. These affect the installations during all phases of a harbor's life, from design to operation. To respond to these complex needs, the SAMOA[18] initiative was born (**Figure 11**), co-funded by Puertos del Estado and the Port Authorities. An integrated system based on CMEMS data has been developed. A total of 10 new high-resolution atmospheric models (1 km resolution, based on Harmonie), 10 wave models (5 m, mild slope model) and 9 circulation models (70 m, ROMS), Sotillo et al. (2019) have been developed and operationally implemented. In terms of instrumentation, SAMOA improved the already existing large network of Puertos del Estado with 13 new meteorological stations and 3 Global Navigation Satellite Systems (GNSSs) associated to the tide gauges. Twenty five ports from 18 Port Authorities will benefit from these new modeling and monitoring developments.

To properly exploit all SAMOA products a dedicated a tool has been developed for the Port Authorities and is currently implemented in 25 ports. This tool, the Environmental Panel Dashboard is based on a web interface[19] and provides easy access to all the information generated by the SAMOA systems, both in real time and in forecast mode. The user can define thresholds for all spatial points inside the application (model points and measuring stations) that are used to trigger alerts. The CMA is also capable of creating customized PDF reports for each forecast point. Additionally, a user-friendly oil spill model and an atmospheric dispersion model have been developed and implemented into the CMA.

Managers of the ports granted access for the tool and defined the levels of user permissions. For example, some users can access visualization but may not have access to the oil spill model, A growing community of 1,250 port users exploit the CMA tool. SAMOA is being improved through the framework of the new SAMOA 2 project. By 2021, a total of 46 ports will have a version of CMA implemented.

SOCIB Innovation, Products, and Services

In terms of innovation, in 2018 SOCIB developed (Heslop et al., 2019) a sector-focused products and services strategy that allowed identification of 10 key user sectors (groups of users with common data interests and needs) which are important to the region (economically/societal benefit) and already receive data of value from SOCIB (e.g., value to decision-making). The implementation of this strategy is now underway and by the end of 2019 the SOCIB website will include a new searchable product catalog, with detailed information on existing products, and new sector-focused products (e.g., for lifeguards on beaches and for the sustainability of Bluefin tuna). Regional ocean observatories have a key role to play in delivering societal benefits from ocean data and research, and the SOCIB efforts concentrate on the coastal component of a future European Ocean Observing System (EOOS).

The sectors and related end users (in brackets) that are now core to SOCIB products strategy are:

- Marine and coastal research (academia, government policy makers and responsible, NGOs)
- Maritime safety (SAR operators, coastguard, oil spill response managers, maritime emergency managers, navy & national security agency)
- Marine sports (recreational sailing, sports sailing/regattas, surfing, diving)
- Beach and coastal communities (citizens, tourists)
- Coastal protection, coastal risks, planning and governance, **Figure 12** (government environmental managers, lifeguards, beach and coastal planners, energy company managers)
- Ports and Shipping (port managers, port pilots, ferry companies/captains, shipping companies/captains, cruise companies/captains)
- Integrated coastal zone and ocean management (ICOM managers, MPA managers, marine managers, water quality operators)
- Sustainable marine ecosystems (fisheries managers, fisheries scientists, commercial fishermen, recreational fishermen, sustainability managers)
- Sustainability of islands and climatic change (government policy, sustainability managers)
- Education and kids (school kids/teachers, higher education kids/ teachers, society)

As an extension to its scientific and societal research and operational activities, SOCIB also undertakes significant outreach work. The SOCIB Outreach Service promotes ocean literacy and raises awareness on the impact of new ocean observing systems on the advancement of knowledge, science-based management and the preservation of marine and coastal resources. The aim is to bring ocean data and ocean science concepts to all citizens and classrooms. Since 2011, SOCIB has participated in 39 events (science fairs, workshops, national contests, etc.) with 20912 participants, and has produced 44 training resources, and educational material, online games and apps for children and teachers[20]. It has been mentioned 621 times in the media.

OceanLab Services

CMCC (Lecce, Italy) has been developing a series of downstream services since the beginning of 2012, based on the CMEMS analysis and forecast products. They are all digital products/services that add value to the generic data available from CMEMS, and address the requirements of the three main maritime and industrial sectors in the Mediterranean Sea.

The first service is dedicated to tourism and the general public. This is a general-purpose visualization service[21] (Coppini et al.,

[18]In Spanish: *Sistema de Apoyo Meteorológico y Oceanográfico a las Autoridades portuarias* - System of Meteorological and Oceanographic Support for Port Authorities.

[19]In Spanish *Cuadro de Mandos Ambiental* - http://cma.puertos.es

[20]mainly online at www.socib.es and more specifically at the outreach portal Medclic, www.medclic.es

[21]www.Sea-Conditions.com

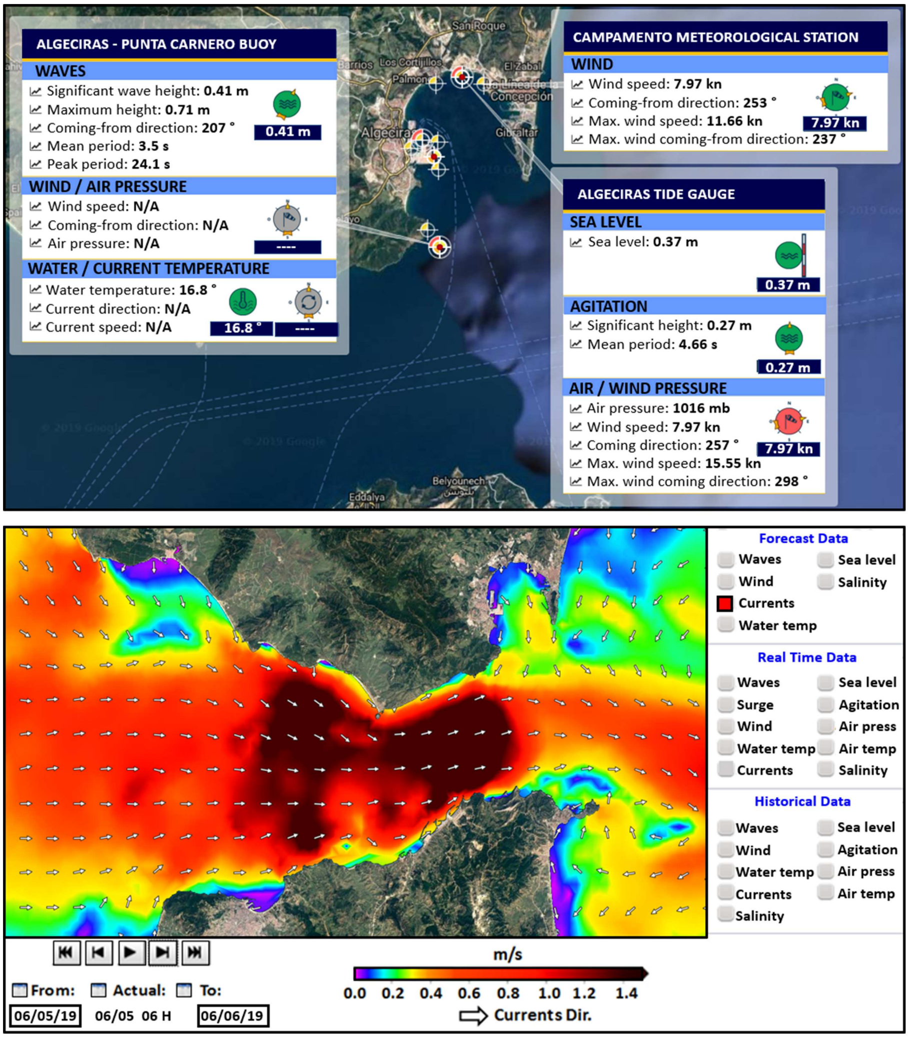

FIGURE 11 | User interface of the SAMOA system at Algeciras Port (Strait of Gibraltar). Real time data (upper panel) and circulation model snapshot (lower panel) (https://cma.puertos.es).

2017) that makes available the analyses and forecasts of ocean and atmosphere on several digital platforms. This is a typical situational sea awareness service that helps tourism operators and recreational users to optimize their work and conduct their activities.

The second service is related to oil spill events and the management of emergencies. Updated forecasts and analyses are made available to an oil spill model (MEDSLIK-II[22]) and an advanced GUI (**Figure 13**) allows the users to predict where the oil will be transported and transformed (Liubartseva et al., 2016). This information is crucial for the planning of actions against accidents and remediation activities.

The third service is dedicated to ship routing for middle-sized vessels. It utilizes real time wave forecasts to find the safest and most efficient route (Mannarini et al., 2016). Users can access the service via an advanced GUI (**Figure 14**). VISIR[23], the model powering this service, has recently been extended to also account for surface ocean currents (Mannarini et al., 2018). This includes an assessment of the contribution of waves and currents to the reduction in the carbon footprints of marine voyages (UN SDG13).

Projects Developing Downstream Services

ODYSSEA (Operating a Network of Integrated Observatory Systems in the Mediterranean Sea) is an EU-funded project[24] aimed at developing, operating and demonstrating an interoperable and cost-effective platform that fully integrates networks of observing and forecasting systems across the Mediterranean basin, addressing both the open sea and the coastal zone. ODYSSEA is a system providing downstream

[22]http://www.medslik-ii.org

[23]www.visir-model.net

[24]http://odysseaplatform.eu

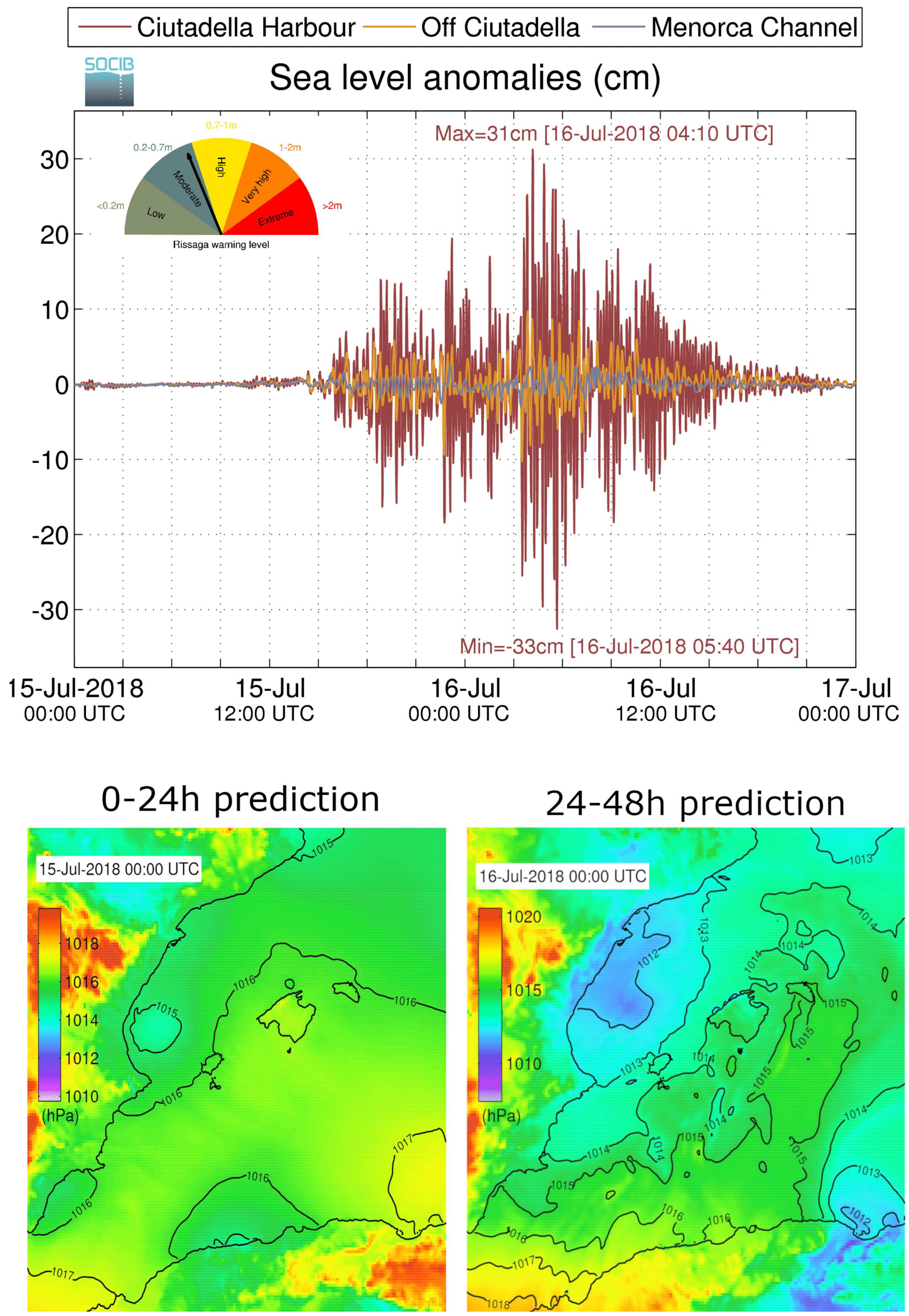

FIGURE 12 | Meteotsunamis BRIFS pre-operational system at SOCIB -www.socib.es---showing sea level anomaly at Ciutadella and Menorca channel and the atmospheric pressure distribution at the surface for the July 16 2018 moderate meteotsunami case. www.socib.es/systems/forecast/brifs.

services to bridge the gap between operational oceanography capacities and the need for information on marine conditions from the community of Mediterranean end-users.

The ODYSSEA platform will be operational by 2021 and will provide easy discovery and access to marine data and derived products to a variety of users, to improve knowledge and decision-making capabilities in the Mediterranean. End-users and stakeholders, internal and external to the Consortium, have been involved from day one of the project in the design, development and operation of the platform and in the data collection and operations of observatories.

At the observatories, on-site observations are combined with remote sensing records, and are then assimilated into high-resolution forecasting models. ODYSSEA can upgrade a novel sensor for microplastic monitoring and resize it to be integrated into a glider, a surface and a bottom on-line monitoring platform. These systems will further integrate submerged cameras and passive acoustic monitoring sensors to expand the operational

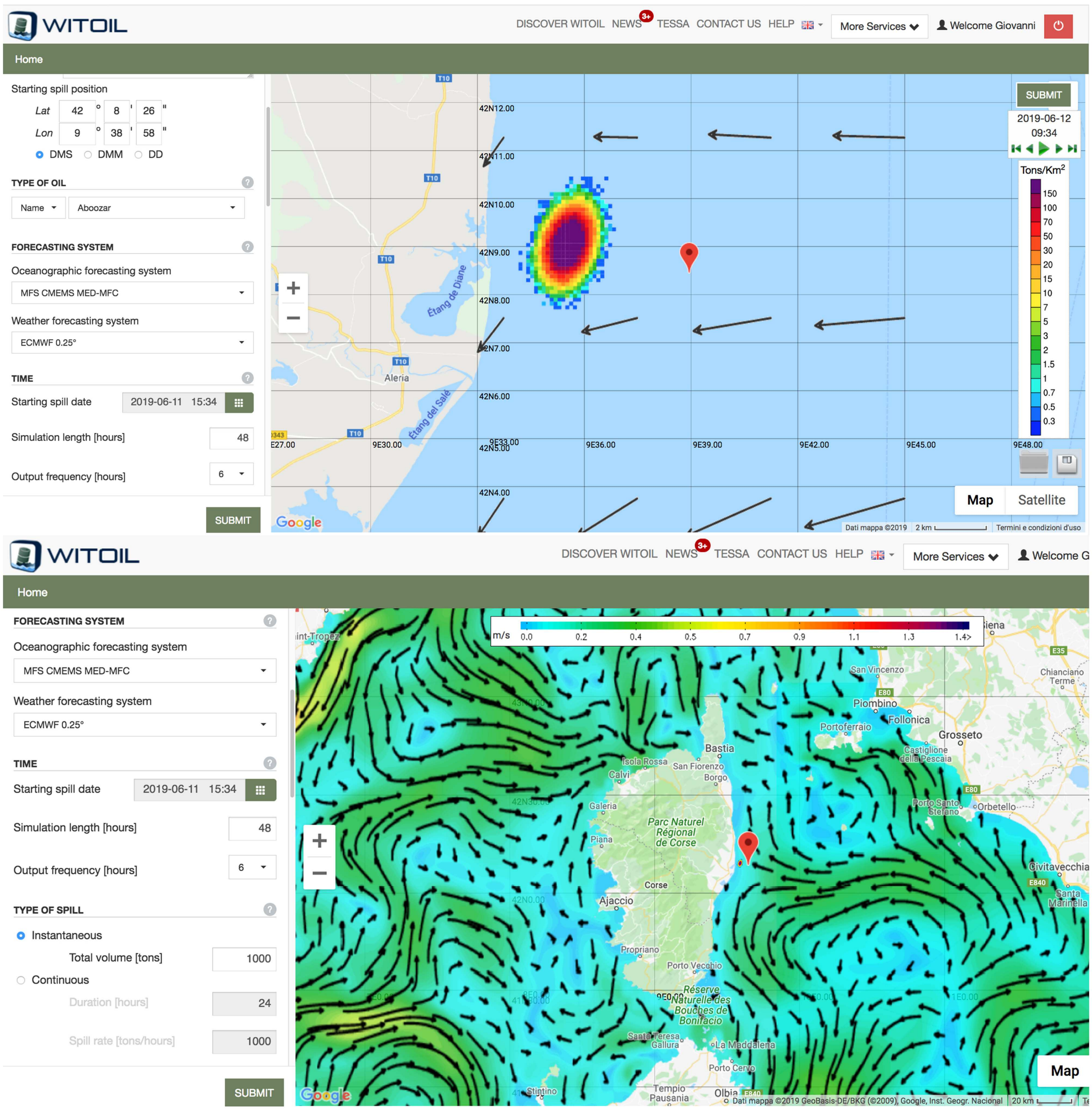

FIGURE 13 | The output and graphics interface for the Oil spill decision support system, called WITOIL. Users can request access by registering http://www.witoil.com/en/join.

capacity of existing systems to include biology, fisheries, etc., and to aid MSFD implementation.

ODYSSEA is aimed at addressing the data gaps that have been identified in the Mediterranean Sea by developing a fully-operational standardized chain of models, comprised of hydrodynamic, wave, water quality, oil spill, fish and mussel population growth components interlinked through a modular interface. Secondary indicators, early forecasts and alarms tailored to user needs will be produced by the platform at Mediterranean and Observatory level, thus supporting the decision-making process of operational users.

GAPS AND PROSPECTS FOR THE NEXT DECADE

Historically, oceanography in the Mediterranean Sea has developed with only limited coordination between the research and environmental institutions involved. The situation today is

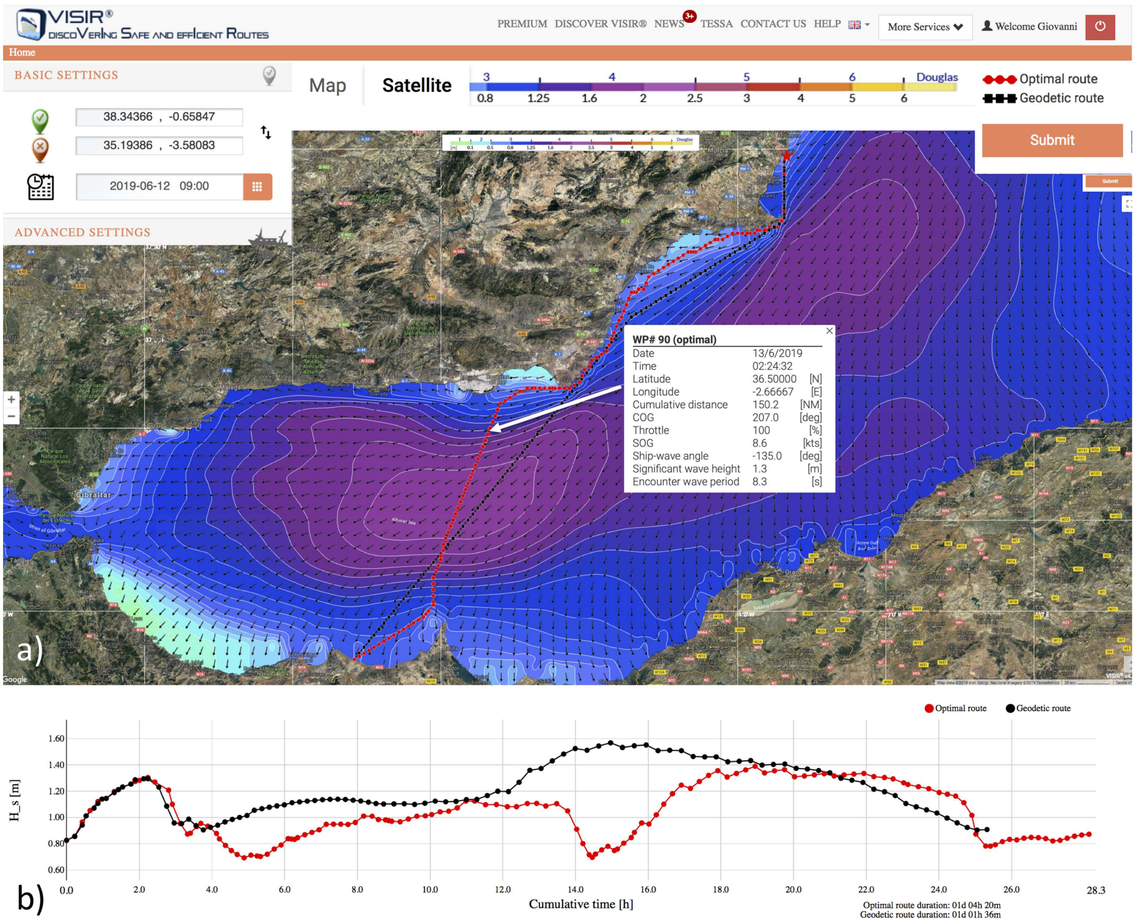

FIGURE 14 | Screenshots from VISIR-nav.com web application: **(a)** Main window, with significant wave height (H_s) in shading and contours, wave direction as black arrows, geodetic route as black waypoint markers (wp), optimal route as red wp. The info-window displays information at the selected wp. Departure wp is marked by a red star. Departure and arrival coordinates and departure date and time are given in the box in the top-left. **(b)** H_s profile along both the geodetic and optimal routes. http://www.visir-nav.com/en/join.

changing, and MONGOOS, in coordination with EuroGOOS, are at the core of this transformation, participating in the designing of strategies that translate into more coordinated systems. A good level of data integration amongst institutions willing to share data has been achieved through a strong MONGOOS coordination and collaborative framework. The provision of information to Copernicus and EMODnet is currently effective and already contributes to the future EOOS strategy. Additionally, the Mediterranean community envisages a strategy of connecting oceanography at different spatio-temporal scales to applications that will give reliable, science-based information to policy makers when deciding on prevention/adaptation/mitigation actions against climate change impacts and environmental problems.

However, the challenges of pollution reduction, climate change, and sustainable fisheries show that this is only the starting point for future integrated observing and forecasting systems. These should consider advanced observing, coupled earth system predicting models and tailored end-user products for societal benefit.

Achieving this higher degree of integration is not a simple or sequential process, and multiple lines of action will be followed. The contribution of MONGOOS will be of paramount importance for this transformation. MONGOOS is the natural working framework for the definition of the requirements of such an integrated system. Additionally, MONGOOS will be instrumental in obtaining the resources required for the transformation. Finally, MONGOOS will contribute to the steering of EOOS, via EuroGOOS, to ensure its objectives are properly aligned with the integration process.

A detailed analysis of the gaps, requirements and future strategies in the Mediterranean and Black Sea region was carried out in May 2015 (Tintoré et al., 2015), after the international workshop entitled "The Kostas Nittis Scientific and Strategic Workshop on a coordinated European observing systems strategy," which was organized to honor the work and memory of this forward-looking scientist. An updated analysis of the gaps can be found in the MONGOOS Science and Strategy plan (Sofianos et al., 2018) and the EMODnet Checkpoint report (Pinardi et al., 2017).

Gaps

To define the gaps in the observing and forecasting system, two components of the ocean value chain can be examined: (1) the basic/core services, which consist of observational and forecasting products; and (2) the downstream products that are customized for specific end-users. These two components have different requirements and specific gaps, and thus different solutions and challenges.

In terms of the basic/core products that can be derived from observations, we have reported some of the gaps in coverage in both space and time for the different platforms, which are mainly due to the lack of observing planning at the Mediterranean Sea basin scale. Bonaduce et al. (2016) demonstrated that the absence of sea level stations along the southern coasts means that estimating the basin mean sea level trend is not possible simply from tide gauges.

From a physical EOV point of view, three-dimensional currents are clearly under-sampled throughout the region. The same applies for waves, salinity and water temperature profiling. From a biochemical EOVs point of view, O_2 content measurements are currently lacking, and so it is not possible to determine whether deoxygenation is an active process at the basin scale. The lack of data in both basins does not adequately describe the seasonality of nutrient concentrations and their spatial distribution, particularly in relation to external sources dependent on human activities.

The under-sampling for both physical and biogeochemical EOVs has been partially analyzed by observing system assessment studies (e.g., Observing System Experiments OSEs and Observing System Simulation Experiments OSSEs, see for instance Oke et al., 2015). These conceptual experiments help to evaluate the impact of specific observations on the EOV core product estimates. Previous work has focused on the impact of gliders (Dobricic et al., 2010; Mourre and Alvarez, 2012; Alvarez and Mourre, 2014; Hernandez-Lasheras and Mourre, 2018), Argo T/S profiles, sampling schemes, float positions, Voluntary Observing Ship XBTs (Griffa et al., 2006; Raicich, 2006; Taillandier and Griffa, 2006; Nilsson et al., 2011; Sanchez-Roman et al., 2017), Ferry Box (Korres et al., 2014) and Fishery Observing System (Aydogdu et al., 2016) platforms. These approaches, extended to the whole set of available multiplatform observations and biogeochemical EOVs, should be part of the common strategy to guide future observing system developments and optimize investments.

The monitoring of fresh water runoff (surface and underground) and land-derived pollution is a serious concern for the Mediterranean Sea. The UN Barcelona Convention has over the past 30 years attempted to monitor pollution and develop an ecosystem approach for conservation and management of fisheries, but much more work is required. Other challenges for the monitoring of pollution in the Mediterranean Sea include the rapidly increasing activities of the oil/gas industry over the last 5 years (Alves et al., 2016) and the increase of maritime transport. We do not have yet an adequate system in support of emergency management even if REMPEC has defined several collaboration agreements with the MONGOOS community.

Gaps in the observing system have been also identified for the downstream products that are customized for specific end-users. The EMODnet Checkpoint (Pinardi et al., 2017) has developed an innovative assessment procedure to detect "data adequacy at the basin scale for downstream products." Seven downstream products, referred to as Challenges, were used: wind farm siting, marine protected areas connectivity, oil spill forecasting, climate and coastal erosion, fishery management, eutrophication, and rivers loading and runoff. Data adequacy has been assessed on the basis of two main set of indicators: availability and appropriateness. Availability entails the evaluation of how the input data sets are made available to Challenges (easily found data sets, data set contained in an INSPIRE Catalog, data policy and its visibility, pricing, delivery mechanism, format of the data and responsiveness of the service). Appropriateness entails measuring the quality of the monitoring data for the Challenge products.

From the availability indicators of 266 input data sets (core products), we found that data adequacy is low for 19 categories of monitoring data variables/environmental characteristics at the basin scale (Pinardi et al., 2017). The Checkpoint results show that over 60% of the core products contributing to the monitoring of the Mediterranean Sea are totally or partly inadequate for their non-compliance with INSPIRE Catalog principles. In addition, above 40% of the input data sets contributing to the monitoring of the Mediterranean Sea are partly or totally inadequate for policy visibility, delivery mechanism, data policy and responsiveness.

Challenges and Solutions

The challenges of developing sustained Mediterranean Sea observing and forecasting systems are mainly institutional, at both national and international levels. At the national level, the links between the research and the operational infrastructures must be reinforced in addition to the links among the ocean research community, the meteorological services and the environmental protection agencies. At the international level the collaborative framework must be strengthened, thus raising awareness about the international and European infrastructure built for basic systems and converging efforts toward best practices and open and free data policies.

The level of international coordination required for enhancing the fitness for use of core/basic products and the fitness for purpose of downstream services is demanding, and requires the societal impact of the activities to be maximized at the international level. The UN SDG targets and indicators offer a primary framework of societal challenges (mitigate and adapt to climate change in the coastal and open ocean areas, ocean health, food production, and disaster risk reduction) that can sustain the maintenance and upgrading of the basic/core infrastructure in the search for solutions.

The recent Ocean Visions Joint initiative[25] began addressing the issue of science-based solutions against the adverse impacts of climate change, and the Mediterranean Sea community is

[25]http://oceanvisions.org/ocean-visions-initiative

beginning to think about this as a potential way forward. At the basis of all these initiatives there has to be the development of knowledge sharing and exchange, free and open data policies and the reinforcement of the science-policy process.

For many of the SDG indicators, the present Mediterranean Sea observational and forecasting system is lacking in space-time resolution for some EOVs. The observational efforts should be strengthened to conveniently monitor the main phenomena occurring in the Mediterranean Sea. In addition, the scientific methodology required to define the right indicators is far from conclusive and further studies are necessary to address this issue. The lack of *in-situ* observations in the Southern Mediterranean and the difficulties accessing these regions is a concern that needs coordinated efforts at an internationally high level. An additional challenge for the Mediterranean Sea is to create synergies between the Marine Strategy Framework Directive, the Barcelona Convention and UN SDGs. Some examples of solutions are those for integrated coastal zone management (Diedrich et al., 2010) and for nature-based solutions in the coastal area (Hendriks et al., 2008), but much more is required.

Some of the challenges are methodological: SDG indicators and solutions should make use of numerical models that integrate the observational data and then interpolate or extrapolate these in time and space. The paradigm of the scientific revolution that has occurred in atmospheric numerical weather predictions has yet to emerge in oceanography (Bauer et al., 2015), and in future the modeling and observational community should work more closely together.

Pinardi et al. (2017) suggest potential solutions to the gaps and challenges listed above. They can be summarized as follows:

1) Strengthen the existing monitoring and forecasting ocean infrastructure (CMEMS, EMODnet, SeaDataNet and the sub-regional systems) by adding to or upgrading it with innovative monitoring technologies and numerical models, including fisheries, habitat, wave data and human activities, and in particular maritime traffic data. Use the MONGOOS framework and coordinate with EOOS through EuroGOOS.
2) Develop a new monitoring strategy for the hydrology and sediment mass balance at the basin scales, while retaining local relevance. Key elements of such new hydrological and sediment mass balance strategies could include the integration of satellites with *in-situ* measurements and the combining of coastal morphodynamics modeling with coastal hydrodynamic predictions.
3) Develop innovative INSPIRE compliant transformation services (cloud-based, etc.) connected to the EMODnet Portals and CMEMS products, based upon an accurate investigation of the stakeholders needs.
4) Strengthen the partnerships between MONGOOS, GOOS, IODE and the atmospheric observing and forecasting community (World Meteorological Organization-WMO) connecting the Mediterranean system to the global met-ocean information infrastructure and its protocols for.

At the basis for future success is maintaining active basic research activities that will address high level scientific goals, which lead to major science breakthroughs, innovations in ocean observations, new operational systems and new paradigms of science-based solutions. Last, ocean literacy and the education of new professionals in the science of ocean operational systems are at the basis of the core infrastructure (Chassignet et al., 2018).

CONCLUSIONS

In this paper we have provided an overview of the status of the Mediterranean Sea observing and forecasting network and the downstream services. The conclusion is that there is a solid base for the core infrastructure and there are advanced examples of downstream services that may have major societal impacts. However, the pathway toward sustainability of this core infrastructure at the level of the Mediterranean Sea basin requires a larger and more intensive collaboration framework to be set up over the next decade, and EOOS could well be a key element in this.

We hope that we have demonstrated that a regional observing and forecasting system can be set up, coordinating national efforts and involving the scientific community in a unique framework. We suggest that the Mediterranean regional observing and forecasting system can be an example of a complex multi-faceted and multi-purpose global ocean observing system as depicted for GOOS (Tanhua et al., 2019). Furthermore, knowing that the Mediterranean is teleconnected with the Atlantic Meridional Overturning Circulation (Volkov et al., 2019) and the Atlantic has obvious impacts in the Mediterranean, it will be particularly important in the future to better interface this regional system to the Atlantic component of GOOS.

The Mediterranean community is ready to contribute to the upgrade of the basic/core infrastructure that will mitigate impacts of climate change, define adaptation strategies and thus reduce the risks of loss of life and property on the coasts and at sea.

AUTHOR CONTRIBUTIONS

JT and NP designed and wrote the paper with significant contributions from the key leading scientists from the Mediterranean Observing and Forecasting Systems and projects (e.g., MOOSE, POSEIDON, ODYSSEA, etc…) and also from MONGOOS, and with specific inputs also from all the other authors.

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OBIS Infrastructure, Lessons Learned, and Vision for the Future

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This mini-review paper analyses the achievements of the Ocean Biogeographic Information System (OBIS), as a distributed global data system and as a community of data contributors and users. We highlight some issues and challenges and identify ways OBIS is trying to address these with developing community standards, protocols and best practices, applying new innovative technologies, improving human capacity through training, and establishing beneficial partnerships. With the release of the second generation of OBIS (OBIS 2.0), we now have a more solid foundation to build improved data processing/integration workflows, new data synthesis routines that add value to OBIS data, and new types of products and applications for scientific and decision-making. The future of OBIS will be in working toward an open and inviting process of co-developing OBIS as a global networked open-source data system that will enable the community to organize, document, and contribute analytical codes that interface directly with OBIS, provide analyses, and share results. The main challenges will be in mobilizing and organizing the scientific community to publish richer and high quality data more rapidly in support of developing robust and timely indicators of status and change on Essential Ocean Variables and Essential Biodiversity Variables.

Keywords: ocean biodiversity, biogeography, research infrastructure, open-access, data and information, science-policy

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INTRODUCTION

Playing a central role in fostering data sharing of marine species observation data since 1999, the Ocean Biogeographic Information System (OBIS) has built the world's most comprehensive database on the diversity, distribution, and abundance of life in the ocean. The OBIS Network is made up of thousands of scientists and data managers employed by hundreds of institutions around the world, who ensure that scientifically researched, collated and published data adhere to FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson et al., 2016). OBIS has built a platform for robust near real-time data integration and curation. It also provides powerful data access and analytical services that streamline the contribution of integrated, quality-controlled datasets into models and forecasts. OBIS has pioneered a solution for managing combined biological and environmental data, including details about sampling effort and methods

(De Pooter et al., 2017). OBIS is now extending beyond species occurrence data, embracing ecosystem Essential Ocean Variables (EOV) in support of the Global Ocean Observing System (GOOS) and the Marine Biodiversity Observation Network (MBON). The identification of the taxonomic components of the EOVs, and the capacity to assimilate and integrate non-taxonomic entities into the global database (i.e., community types like macroalgae) will contribute to their efforts to build a sustained, globally coordinated observing system on the status and trends of marine biodiversity and habitats (Benson et al., 2018).

The world agreed on the Aichi biodiversity targets (2011–2020) to better understand and predict biodiversity dynamics, that is how biological diversity underpins ecosystem function and how the provision of ecosystem services are essential for human well-being. With the recent announcement by the Intergovernmental Panel on Climate Change (IPCC) indicating that climate change must be addressed by 2030 to avert major catastrophic changes to global and marine ecosystems, it is clear that time is limited to more adequately understand and protect marine biodiversity.

The success of bringing millions of marine species observations into the public domain is a major achievement. Through FAIR access to data, OBIS provides equitable access and benefits to research, biodiversity conservation management and policy making, and also enhances international collaboration, for which OBIS is recognized by many global organizations including the United Nations General Assembly. OBIS is requested to support several international processes such as those under the UN Regular Process (World Ocean Assessment), the Convention on Biological Diversity (CBD) and the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES). OBIS will have an active role providing open and timely integrated biodiversity and habitat records for the United Nations Educational, Scientific and Cultural Organization (2017), that will be crucial to its success.

CHALLENGES AND OPPORTUNITIES, A VISION FOR 2030

After two decades of OBIS we can reflect on its achievements, where it performed well and where it needs continuous improvement. We can look ahead and identify challenges and opportunities for OBIS to respond to new demands for ocean data and information services. We plan to develop OBIS as a critical component in accelerating the pace of scientific exploration and discovery in response to the urgent needs imposed by our changing planet.

One critical aspect of OBIS is that despite two decades, including the Census of Marine Life, and integrating over 50 million records, widespread gaps in taxonomy, space, and time still remain (Müller-Karger et al., 2018a). This reflects the bias of sampling effort worldwide, but still half of the records added to OBIS after 2015 date before 2000, illustrating significant effort spent on data archeology – digitizing data from before OBIS existed (Müller-Karger et al., 2018b). Establishing robust baselines against which current and future change can be detected is important but detecting the most recent changes using OBIS is currently difficult due to the typical delay in processing and reporting recent observations (<5 years) as shown by an overall decline in data in OBIS after 2010 (Müller-Karger et al., 2018b). It is vital to accelerate data availability through OBIS by building direct connections with marine biodiversity monitoring networks and other near real-time observation activities.

The scientific publishing track record of OBIS is growing with over 100 scientific papers per year referring to OBIS. Three chapters of the first United Nations World Ocean Assessment (The Group of Experts of the Regular Process, 2017) used data from OBIS, and several recent high-impact papers provide new insights in global marine species richness patterns (Chaudhary et al., 2016, 2017; Saeedi et al., 2017; Menegotto and Rangel, 2018), biogeographical classifications (Costello et al., 2017; Sutton et al., 2017), and projected biodiversity change linked to climate (Dornelas et al., 2014; Bowler et al., 2017; Griffiths et al., 2017).

State of the Framework

Due to the different nature and interests of the potential users, the value proposition from OBIS could vary, from data producers (scientific institutions) to data analysts (research scientists) to information product end users (policy makers and managers). We work to characterize and understand our global customer base through system monitoring, user engagement, and regular independent review, developing plans for action through the OBIS Steering Group. The following sections present the principles of the core design of OBIS.

International Data Management Best Practices

The breadth of the OBIS Network across such a wide swath of the marine biodiversity science community has been a core driver in adoption of and contribution to international standards and practices in research data management. The FAIR Principles represent a culmination of many years of work to suggest a core set of practices that OBIS ascribes to and has been implementing for some time. The Group on Earth Observations, an organization with which OBIS is closely aligned, adopted 10 Open Data Principles to promote and to encourage best practices and maximize the potential for appropriate re-use and combination with other data sources.

Following these and other relevant guidelines and best practices, OBIS provides the following core values:

- Data standards developed through the Biodiversity Information Standards (TDWG) body that help data producers decide on data attributes and parameters for their data collection efforts.
- A data repository framework consisting of distributed nodes and a central hub to submit data, cite it, and advertise it for use, achieving compliance with national or institutional requirements for releasing open data.

- Support and training in data management techniques, methods, and tools developed by the network for data management and analysis.
- A thriving research community developing biodiversity data analysis techniques.

Evolving Data Types

New and innovative methods for observing marine biodiversity such as the Imaging FlowCytobot (Olson and Sosik, 2007) and genomics techniques for assessing biodiversity (Bourlat et al., 2013) are currently being used to increase the observation and measurement coverage of the marine environment. Where possible, OBIS seeks to develop alliances leading to intelligent data interchange methods such as a developing partnership with the Global Coral Reef Monitoring Network. OBIS serves as the nexus where these new methodologies can integrate their data in a rich and standard format, and the OBIS community can help provide mapping across diverse variables to calculate metrics and produce biodiversity indicators.

Ocean Biogeographic Information System has provided leadership in this area through enhancements to the Darwin Core Standard to allow documentation of qualitative or quantitative information about both the sampling event and the species observation within that sampling event (De Pooter et al., 2017). This work has broadened the capacity of integrating information from a variety of sampling methods and instruments, enabling OBIS to leverage richer datasets containing other environmental observations and measurements. Previously, when measurements such as water temperature, salinity, and wind speed were collected in association with species observations, those data were difficult to link together. Now, it is possible to ingrate these datasets syntactically and enhance the connection between them through focused attention on the development and implementation of robust vocabularies. This new schema will provide the ability to understand the context of the origin of the data and explore the relationship of the biodiversity records with accompanying environmental variables.

Using this new schema, OBIS nodes are able to document data that were previously difficult to integrate. For example, animal tracking and telemetry data managers are using the new OBIS schema on machine recorded observations and have developed and documented requirements specific to this type of data using the new schema. Similarly, data from FlowCytobots are being assessed and documented. Current research and development efforts are beginning on the most effective ways to encode observations and measurements where the focal entities are operational taxonomic units or habitats made up of groups of organisms rather than a single, identifiable taxon.

Technical Infrastructure

The OBIS infrastructure is fundamentally distributed in that it consists of source data repositories at OBIS Nodes where core data management is conducted. OBIS Node data is harvested into a central index where final data assessment processes are conducted, and third-party information is integrated. OBIS follows an "API-first mindset," meaning that everything starts with a robust Application Programming Interface (API) that then serves the needs of a web portal, mapping tool, and open source/free scientific programming packages (R and Python). The power of this approach is in its ability to mobilize and enable the broader global community in building their own tools and capabilities on an open framework.

Recent developments and the release of OBIS 2.0 enables the following major capabilities:

- Near real-time data integration from OBIS Nodes – as soon as OBIS Nodes advertise the availability of new or updated data, the OBIS system begins automated processing to ingest data and completes integration routines in a timely manner.
- The ability to scale the system to hundreds or thousands of new datasets and millions of new records while providing timely results for queries, data access (download and streaming), and products (analytics and indexes).
- The ability to integrate environmental variables in addition to biological observations and to fully leverage this new type of data in queries, data access, and products.
- Data management support is provided at a foundational level for OBIS Node Managers through the obistools R Package (Bosch et al., 2018).
- Improvements on the real-time analytics capability of OBIS to directly convert raw data into EOV and into values of biodiversity indices and indicators, starting at the API level to support science end-users through the rOBIS package (Provoost and Bosch, 2018) and custom apps/portals along with a flexible and ever evolving set of reports through the OBIS portal.
- Improvements on the full visibility of the OBIS Network by persistently linking OBIS Nodes, data provider institutions, and individual contributors (data providers, authors, etc.) together such that each entity is cited and their full contribution to OBIS easily accredited.
- New portal and map explorer capabilities built to scale as data volumes continue to expand.

Continuous Data Assessment and Enhancement

Data generated through so many different campaigns and data collection efforts through time and changing practices are inevitably of varying overall quality and completeness. Part of the role of OBIS is to continually assess inbound data for alignment with standards and compliance to particular conventions used within the community to aid users in data selection and analytical uses (Vandepitte et al., 2015). OBIS performs a battery of tests on new and updated data, records metrics from these processes, and uses the values for intelligent filters in the portal, API, and other interfaces. The adopted approach leads toward evaluating data as to fitness for purpose, keeping track and exposing all QC tests performed on every record, rather than making judgments about quality.

Part of the real power in integrating hundreds of disparate datasets with a common standard is an ability to reach out to related information systems linkable because of the points of integration in areas such as taxonomy, space, time, and other variables. These variables allow OBIS to write intelligent information linking processes that pull in useful information from third party sources from the World Register of Marine Species to regulatory context and information about marine regions. This information is linked and incorporated into the OBIS system in real time and continuously as data are added and updated.

Capacity Building

The organizational structure of OBIS and its placement within UNESCO's IOC provides a mandate and institutional framework for continual capacity building as a core function. More effort and as many resources as possible are put into developing the core capacity of the OBIS Nodes than building the central infrastructure. The OBIS secretariat at the IOC Project Office for IODE in Belgium allies closely with the Flanders Marine Institute and other scientific institutions in leveraging core technical capabilities such as central source data hosting, provided free of charge to OBIS Nodes who do not have these capabilities in their host institutions. Close alignment with the OceanTeacher Global Academy (OTGA) provides advantages in developing and providing training courses in data management, data analysis, decision support, and other areas of importance to OBIS.

Ocean Biogeographic Information System Nodes provide training courses in English, French and Spanish at the OTGA regional training centers in Belgium, Colombia, Kenya, Malaysia, and Senegal, with course materials available online for use under CC-BY-NC-SA license terms. Training has focused on working with students who have a basic knowledge of data management practices and tools from basic spreadsheet methods to R scripting such that skills can be immediately applied to the most critical areas of learning this particular

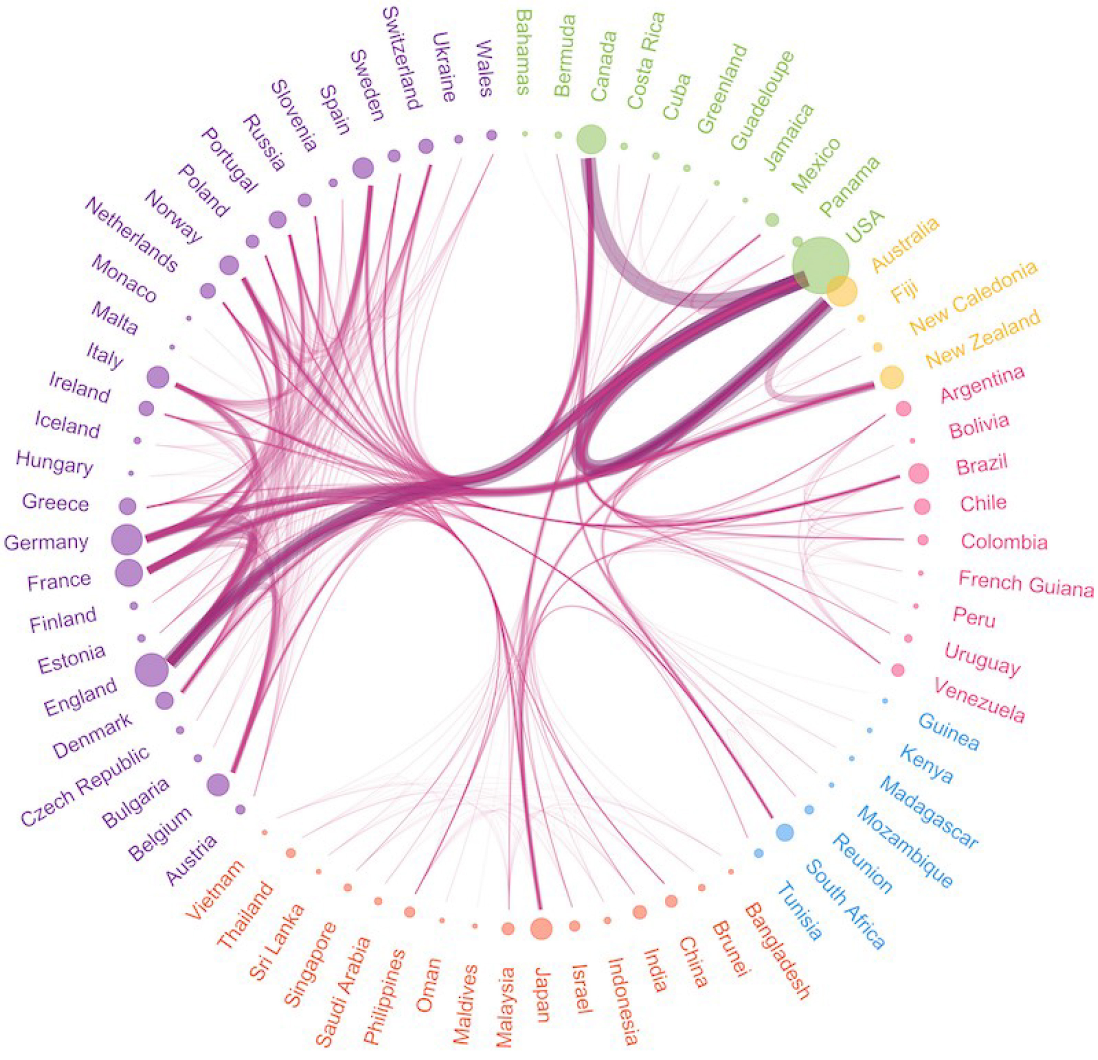

FIGURE 1 | Based on a bibliographic study in collaboration with the library of the Flanders Marine Institute, 2700 scientists from 73 countries collaborated on >1000 papers citing OBIS. This figure shows the connections between the countries in co-authoring these papers.

domain. Course modules cover both data management and the basics of data analysis such that trainees can either use the skills on their own or assist institutional research scientists and other users in working with the data in scientific analysis.

We see multiplication of training efforts catalyzed through the OceanTeacher online Moodle platform by various institutions linked to the national OBIS nodes which in the last 2 years organized OBIS training courses in Chile, Ecuador, Brazil, Germany, Kenya, Mexico, Russia, Iran, and the United States. These efforts represent direct return on investment to the OTGA and its funders, increasing the distribution and development of knowledge on marine data management and use worldwide.

In addition to formal training, the OBIS Network is constantly working to build capacity through a variety of other services to the community. These often include relatively low cost and simple steps such as providing guidance on ways to leverage third party and readily accessible tools to publish source data and receive Digital Object Identifiers for citation purposes. While readily known in many developed parts of the world, these types of services are often not as well known in developing countries, and the OBIS Network provides an opportunity for knowledge sharing in many subjects.

Figure 1 shows the amount of collaboration between nearly 3,000 scientists from 70 countries in publishing over 1,200 papers citing OBIS. This clearly illustrates strong connections between countries to develop new science making use of this open data resource, but it also demonstrates emerging North-South and South-South collaboration, which are areas OBIS wish to improve further.

State of the Data

Of all described marine species today (243,000 in the World Register of Marine Species), about half of them have a distribution record in OBIS. Furthermore, 56% of the species in OBIS have less than 10 records, which indicates that the bulk of the data in OBIS represents well-known, easily monitored species (**Figure 2**). Also, there is an important bias toward the shallow coastal areas and the surface layers of the ocean, creating a gap in the midwater pelagic environments and deep-sea communities (Webb et al., 2010). Despite the fact that rare or under-reported species can occupy important local ecological niches and therefore should not be neglected in biodiversity assessments, incidental observations rarely end up in big monitoring or research datasets and hence are missing in global data systems such as OBIS. At best, new species records or invasions are published in the literature (often gray literature). Those few observations can sometimes provide early indicators of change, and often fill crucial gaps which can influence distribution models and forecasts or provide important insights in the distributions of marine species. There is growing interest from

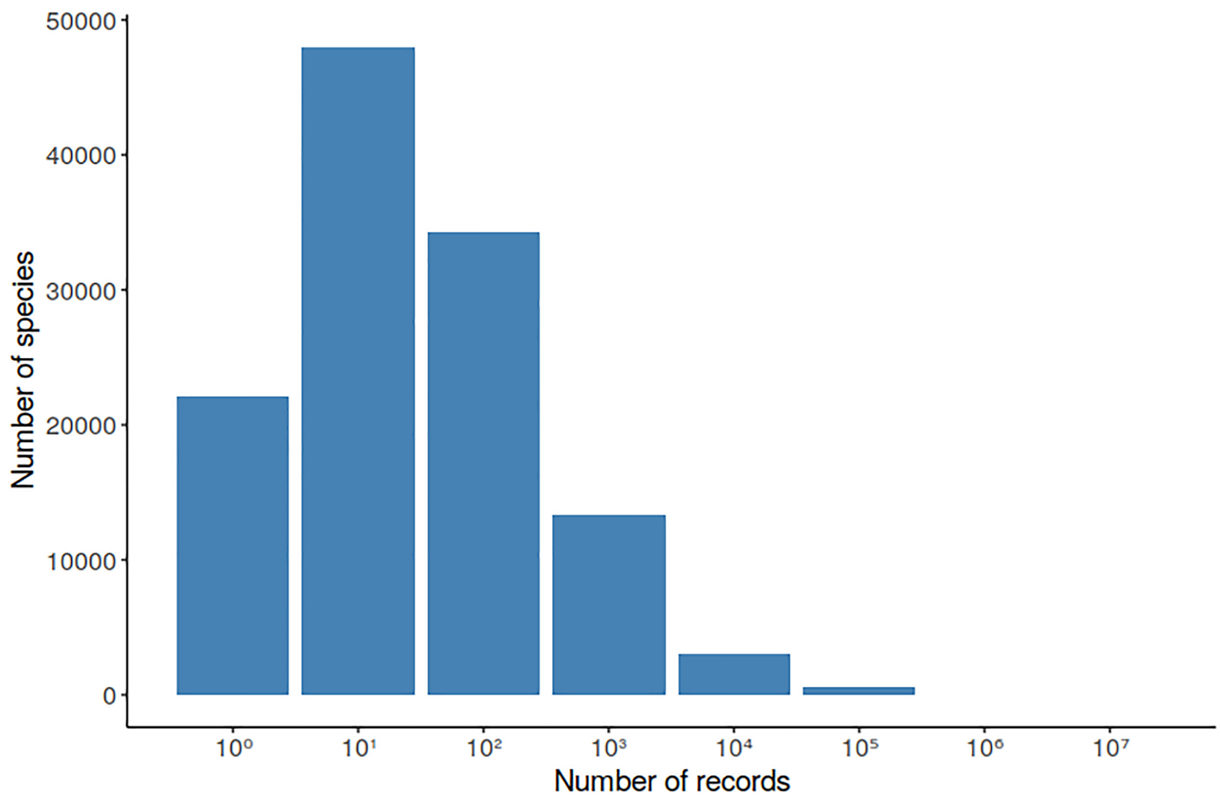

FIGURE 2 | Number of taxa identified at species level in OBIS by number of records in the database. More details about the distribution of the records by taxa and statistics on quality issues can be found on the OBIS statistics page, which is updated with every new record published in OBIS (https://obis.org/statistics).

individual scientists who wish to share biodiversity observation records through OBIS directly, be able to immediately validate and publish those records, and subsequently retrieve a more complete and robust dataset for analysis. OBIS is developing a simple online data entry and editing tool that will allow individual scientists to submit these incidental records without the need to worry about whether they follow agreed standards or the need to organize data in the right formats which is identified as the main challenge of data sharing in a large survey published by Nature (Stuart et al., 2018). This will enable the network of data contributors to grow by lowering the barrier of entry.

RECOMMENDATIONS AND CONCLUSION

Modern society requires robust and timely information in order to generate a better understanding of the marine environment and make better informed decisions in management and conservation. Having a system that dynamically navigates the relationships between disparate data, synthesizing a set of useful information products is a vital asset in analyzing decisions. But the effective use of the system is only achieved by a carefully planned training program that brings together different levels of users and different needs into a common platform.

Countries should openly communicate on their policies regarding the public release of environmental data and increase the implementation of data publication mechanisms through active encouragement and if necessary, enforcement. In some countries, project funding depends on data released in the public domain, or a scholar's performance is measured taking into account dataset citations along with peer-reviewed papers. Measuring performance in this paradigm has well-established methods and practices. Measuring the impact of science on policy and resource management decisions is less clear. New metrics must be developed considering the impact of contributions of data and products on the sustainable use and conservation of our marine environment. OBIS promotes the establishment of a virtuous cycle between data and knowledge generators, data integrators and synthesizers, and policymaking stakeholders.

AUTHOR CONTRIBUTIONS

WA, EK, and RB wrote the major part of the manuscript, with additional contributions from PP, HS, AB, LB, and AP. PP and EK created the figures.

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Observational Requirements for Long-Term Monitoring of the Global Mean Sea Level and Its Components Over the Altimetry Era

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Present-day global mean sea level rise is caused by ocean thermal expansion, ice mass loss from glaciers and ice sheets, as well as changes in terrestrial water storage. For that reason, sea level is one of the best indicators of climate change as it integrates the response of several components of the climate system to internal and external forcing factors. Monitoring the global mean sea level allows detecting changes (e.g., in trend or acceleration) in one or more components. Besides, assessing closure of the sea level budget allows us to check whether observed sea level change is indeed explained by the sum of changes affecting each component. If not, this would reflect errors in some of the components or missing contributions not accounted for in the budget. Since the launch of TOPEX/Poseidon in 1992, a precise 27-year continuous record of sea level change is available. It has allowed major advances in our understanding of how the Earth is responding to climate change. The last two decades are also marked by the launch of the GRACE satellite gravity mission and the development of the Argo network of profiling floats. GRACE space gravimetry allows the monitoring of mass redistributions inside the Earth system, in particular land ice mass variations as well as changes in terrestrial water storage and in ocean mass, while Argo floats allow monitoring sea water thermal expansion due to the warming of the oceans. Together, satellite altimetry, space gravity, and Argo measurements provide unprecedented insight into the magnitude, spatial variability, and causes of present-day sea level change. With this observational network, we are now in a position to address many outstanding questions that are important to planning for future sea level rise. Here, we detail the network for observing sea level and its components, underscore the importance of these observations, and emphasize the need to maintain current systems, improve their sensors, and supplement the observational network where gaps in our knowledge remain.

Keywords: sea-level change, satellite altimetry, GRACE (gravity recovery and climate experiment), Argo float array, sea level budget

INTRODUCTION

Sea level varies over a broad range of spatial and temporal scales in response to a large variety of physical processes. On time scales ranging from a few years to several decades (the time scale of interest here), sea level changes are caused by external forcing factors of natural origin (e.g., changes in solar irradiance and volcanic eruptions) or induced by human activities through Green House Gas (GHG)-related global warming. Natural variability inside the climate system, for example related to coupled atmosphere-ocean perturbations such as El Nino-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), or Pacific Decadal Oscillation (PDO) also cause interannual to multidecadal sea level variations at regional and global spatial scales. On these time scales, deformations of the solid Earth and changes in the gravity field caused by mass redistributions occurring inside the Earth or at its surface also produce regional sea level variations.

In this paper we discuss the sea level budget, i.e., the observed global mean sea level and its various contributions (ocean thermal expansion, land ice melt, land water storage change), focusing on the altimetry era (1993 to present). Tide gauge instruments located along coastlines have for more than a century provided invaluable information on historical sea level evolution. However, it is only recently, since the early 1990s, that sea level can be measured with quasi global coverage, owing to the constellation of altimeter satellites. Data availability from the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004) and from the Argo system of autonomous profiling floats (Riser et al., 2016) since ∼2005 also allows quantifying the various components causing global mean sea level changes, hence assessing the closure of the sea level budget. Here, we present the various observing systems used to study the sea level budget over the altimetry era. We also address requirements for sustained observations as well as new or complementary observing systems to improve our knowledge of all components of the sea level budget. Regional and coastal sea level are the topic of other white papers (Benveniste et al., 2019; Ponte et al., 2019), thus they are not addressed here.

GLOBAL MEAN SEA LEVEL AND ITS COMPONENTS

Sea Level Budget

Present-day interannual to decadal changes in sea level result from different contributing factors that themselves arise from changes in the ocean, the terrestrial hydrosphere, the cryosphere, and the solid Earth. Indeed, global mean sea level changes result from ocean thermal expansion and ocean mass changes due to ice mass loss from the Greenland and Antarctica ice sheets, melting of glaciers, and changes in land water storage. At regional scale, spatial trend patterns in sea level result from the superposition of "fingerprints" caused by different phenomena: changes in sea water density due to changes in temperature and salinity (so-called "steric" effects), atmospheric loading, and solid Earth's deformations and gravitational changes in response to mass redistributions caused by land ice melt and land water storage changes (called "static" effects; Stammer et al., 2013). The land ice melt-related static factor comes from two processes: the viscoelastic response of the solid Earth to last deglaciation, also called Glacial Isostatic Adjustment (GIA), and the elastic deformation of the Earth's crust due to ongoing land ice melt, and associated changes in the gravitational field of the planet. The static factors—mostly inferred from modeling—give rise to complex regional patterns in sea level change (Bamber and Riva, 2010; Tamisiea, 2011; Spada, 2017): sea level drop in the immediate vicinity of the melting bodies but sea level rise in the far field (e.g., along the coast of northeast America and in the tropics). The GIA effect depends on Earth's mantle viscosity structure and deglaciation history (Lambeck et al., 2010; Peltier et al., 2015) while the response of the solid Earth to ongoing land ice melt essentially depends on the elastic structure of the Earth, especially the lithosphere as well as amount and location of ice mass loss.

In the following, we call GMSL (t) temporal variations of the global mean sea level where t represents time.

GMSL(t) is classically expressed by the sea level budget equation:

$$\mathrm{GMSL(t)} = \mathrm{GMSL_{steric}(t)} + \mathrm{GMSL_{mass}(t)} \quad (1)$$

where $\mathrm{GMSL_{steric}(t)}$ and $\mathrm{GMSL_{mass}}$ (t) represent the global steric sea level change (i.e., the contributions of ocean thermal expansion and salinity changes) and the change in mass of the oceans, respectively. Note that in terms of global average, salinity does not contribute to the GMSL.

The total water mass of the climate system is conserved. Thus, the mass term can be written as:

$$M_{\mathrm{ocean}}(\mathrm{t}) + \mathrm{M_{Glaciers}(t)} + \mathrm{M_{Greenland}(t)} + \mathrm{M_{Antarct.}(t)} + \mathrm{M_{LWS}(t)} + \mathrm{M_{Atm}(t)} + \text{missing mass terms} = 0 \quad (2)$$

In equation (2) above, $\mathrm{M_{ocean}}$ (t), $\mathrm{M_{Glaciers}(t)}$, $\mathrm{M_{Greenland}(t)}$, $\mathrm{M_{Antarct.}(t)}$, $\mathrm{M_{LWS}(t)}$ and $\mathrm{M_{Atm}(t)}$ correspond to changes in mass of the ocean, glaciers, Greenland and Antarctica

Ice Sheets, as well as changes in land water storage (LWS) and atmospheric water vapor content. Snow mass changes are generally included in the land water storage term. Changes in atmospheric water vapor content are supposed to be small and are currently neglected. Missing mass terms could include for example water released by permafrost thawing. The latter contribution is also assumed to be negligible.

- Temporal changes in the thermal and mass components of the above budget equation directly cause variations of the global mean sea level. Study of the sea level budget thus provides constraints on imperfectly known contributions, e.g., the deep ocean below 2,000 m being undersampled by current observing systems or the still-uncertain land water storage component (WCRP Global Sea Level Budget Group, 2018). Study of the sea level budget also provides information on the total ocean heat content, from which the Earth's energy imbalance can be deduced (e.g., Von Schuckmann et al., 2016; Meyssignac et al., 2019).
- The Global Climate Observing System (GCOS, 2011) has defined a set of ∼50 Essential Climate Variables (ECVs) to be monitored on the long term to improve our understanding of the changing climate. 26 ECVs are observable from space. The sea level ECV is one of them. The global sea level indicator and the global sea level budget are now included in the annual Statement on the State of the Global Climate delivered by the World Meteorological Organization (WMO (World Climate Organization), 2019) to inform decision makers and society about the global climate as well as weather and climate trends at global and regional scales.

Summary of Recent Results on the Global Mean Sea Level Budget

A number of previous studies have studied the global mean sea level budget over different time spans, in particular over the high-precision altimetry era, using different data sets (e.g., Cazenave et al., 2009; Church and White, 2011; Leuliette and Willis, 2011; Llovel et al., 2014; Chambers et al., 2017; Chen et al., 2017; Dieng et al., 2017; Nerem et al., 2018). Assessments of the published literature have also been performed by successive IPCC (Intergovernmental Panel on Climate Change) reports (e.g., the 5th Assessment Report, Church et al., 2013). A recent effort involving the many groups worldwide was conducted in the context of the World Climate Research Programme (WCRP), to assess the global mean sea level budget using all available data sets for all terms of the sea level budget (WCRP Global Sea Level Budget Group, 2018). Another ongoing initiative is the ESA Climate Change Initiative (CCI) Sea Level Budget Closure project, which analyzes, in an integrative context, recent results obtained by the ESA CCI programme for the sea level, glaciers and ice sheet ECVs (with additional consideration of the ocean thermal expansion component utilizing the CCI Sea Surface Temperature ECV), and assesses to what degree the global mean sea level budget is closed (Horwath et al., 2018).

MEASURING SEA LEVEL BY ALTIMETER SATELLITES

Until the early 1990s, sea level rise was measured by tide gauges, which are unevenly distributed in space and time (**Figure 1**). The tide gauge records suffer from data gaps and are contaminated by vertical land motions (VLMs). Thus depending on the processing methodology and adopted corrections for the VLMs, scattered estimates of the Twentieth century sea level rise have been proposed, ranging from 1.2 to 1.9 mm/year (Church and White, 2011; Jevrejeva et al., 2014; Hay et al., 2015; Dangendorf et al., 2017).

Since the beginning of 1993, sea level is now measured by a succession of altimeter satellites with quasi global coverage. In effect, the launch of the TOPEX/Poseidon mission in August 1992 marked the beginning of the era of high-precision satellite altimetry for applications to oceanography and climate research. The constellation of high-precision satellite altimeters is shown in **Figure 2**.

Outside Europe, several groups routinely process the altimetry data to provide sea level products at global and regional scales. These include:

1) University of Colorado (CU Release 3; http://sealevel.colorado.edu/).
2) Goddard Space Flight Center (GSFC version 2; https://sealevel.jpl.nasa.gov/).
3) National Oceanographic and Atmospheric Administration (NOAA; http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_global.php).
4) Commonwealth Scientific and Industrial Research Organization (CSIRO; www.cmar.csiro.au/sealevel/sl_data_cmar.html).

In Europe, altimeter sea level products have been processed by the CNES/CLS DUACS altimeter production system since 2001 (https://duacs.cls.fr) and distributed since 2003 through the AVISO+ CNES Satellite Altimetry Data portal (www.aviso.altimetry.fr/en). Since 2015, the whole processing, operational production and distribution of the DUACS along-track (level 3) and gridded (level 4) altimeter sea level products have been taken over by the European Copernicus Program (with the support of EUMETSAT for Sentinel-3 products). The DUACS production system delivers sea level products for two different Copernicus services:

- The Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu/): the sea level products focus on the retrieval of mesoscale signals with the best estimate and sampling of the ocean at each moment and are thus dedicated to ocean modeling and ocean circulation analysis. Both delayed-time and near-real-time products are distributed.
- The Copernicus Climate Change Service (C3S, https://climate.copernicus.eu/): the altimeter products focus on the monitoring of the long-term evolution of sea level for climate applications and the analysis of ocean/climate indicators. These delayed-time products have been

FIGURE 1 | Tide gauge coverage with > 40-year-long records (source: PSMSL; https://www.psmsl.org/products/data_coverage/).

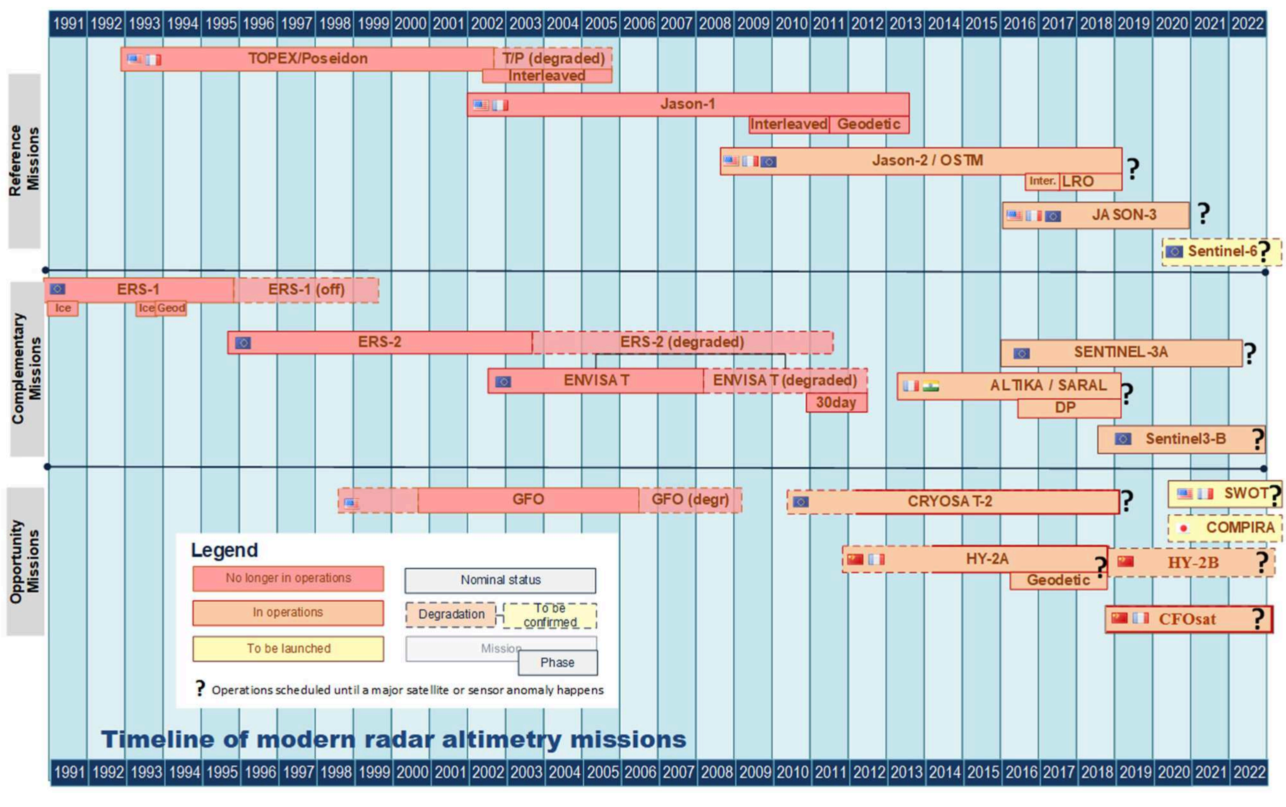

FIGURE 2 | Constellation of high precision altimeter satellites; Status in April 2019.

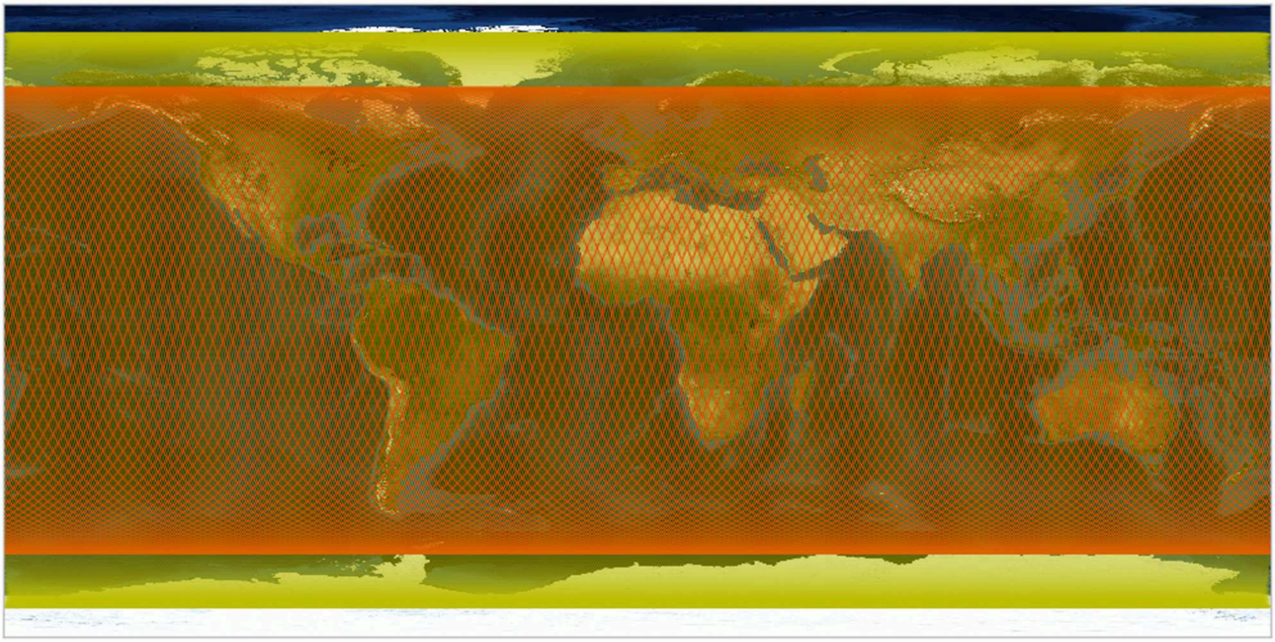

FIGURE 3 | Coverage of high-precision altimetry missions in repeat orbit (red curves correspond to Jason orbits, while yellow curves correspond to Envisat/SARALAltika orbits).

designed with a focus on homogeneity and stability of the record.

The main differences between the CMEMS and C3S altimeter sea level products concern: (i) the number of altimeters used in the satellite constellation: all available altimeters are considered in the CMEMS products whereas a steady number (two) of altimeters are included in the C3S products; and (ii) the reference field used to compute sea level anomalies: an optimized reference field (mean profiles of sea surface heights) is used for missions with a repetitive orbit in CMEMS whereas an homogeneous mean sea surface is used for all missions in C3S.

All these DUACS altimeter sea level products were previously known as "AVISO" products and should now be called "Copernicus" products. More details on their specification are available in the product user manuals of the respective Copernicus services as well as in Pujol et al. (2016) and Taburet et al. (in press). The AVISO+ portal still includes ocean monitoring indicators (such as the GMSL evolution), added-value and pre-operational research products (https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products.html).

In addition, from 2011 to 2017, the ESA Sea Level Climate Change Initiative (SL_cci, http://www.esa-sealevel-cci.org/) project has developed new optimized altimeter algorithms that improve the homogeneity and stability of the sea level record. This has led to the production of a delayed-time sea level product including nine altimeter missions and covering the period 1993–2015 (Ablain et al., 2015, 2017a; Quartly et al., 2017; Legeais et al., 2018). The last version of the operational Copernicus sea level products (DT-2018 reprocessing) has benefited from the SL_cci developments. In this context, the operational production of the climate-oriented sea level products by the Copernicus climate service (C3S) extends the sea level time series.

Among the different ocean monitoring indicators, the global mean sea level can either be derived by directly averaging the validated along-track data or averaging gridded data based on optimal interpolation of the along-track data. The long-term stability of the GMSL is ensured by the TOPEX-Poseidon, Jason-1, Jason-2, and Jason-3 reference missions. They are thus essential for the computation of the sea level trends. They cover the ±66° latitude band and have a repeat cycle of 10 days. Other complementary and opportunity missions (ERS-1, ERS-2, Envisat, SARAL/AltiKa, HY-2A, Sentinel-3A & 3B, and CryoSat-2) improve the geographical sampling of mesoscale processes by improving the spatiotemporal resolution, provide high-latitude coverage (up to +/−82°), and increase the sea level accuracy (**Figure 3**).

Among the above-listed different international groups that compute the GMSL, each one has its own processing system, considers different satellite missions, applies slightly different geophysical corrections, and has developed different strategies for the data editing and gridding. The GMSL time series derived from the European products (averaging of along-track measurements of the reference missions for AVISO+ and averaging of multi-mission merged gridded CMEMS or C3S products) are considered to be identical since the same altimeter standards are used to compute the sea level anomalies, and the long-term stability is ensured by the same reference missions. The remaining observed GMSL differences are not significant given the uncertainty considered on different scales (Ablain et al., 2015).

THE 26-YEAR-LONG ALTIMETRY-BASED GLOBAL MEAN SEA LEVEL

The altimetry-based GMSL record is shown in **Figure 4**. It is based on the CCI multi-mission merged gridded sea level data up to December 2015 extended with the CMEMS and near-real-time data from Jason-3. The time series is corrected for GIA by subtracting a −0.3 mm/year value from the trend (Peltier, 2004). The seasonal signal is removed by fitting sinusoids of 6- and 12-month periods to the data. The first 6 years of the GMSL record are corrected for an instrumental drift that affects the TOPEX-A altimeter of the TOPEX/Poseidon mission, using the correction proposed by Ablain et al. (2017b). Over the 26-year long time span (January 1993 to February 2019), the mean rate of sea level rise amounts to 3.15 ± 0.3 mm/year, with an acceleration of 0.10 ± 0.04 mm/year^2 (1-σ errors based on Ablain et al., 2019). This acceleration value agrees well with Nerem et al. (2018)'s estimate, of 0.085 mm/year^2, after removing the interannual variability of the GMSL.

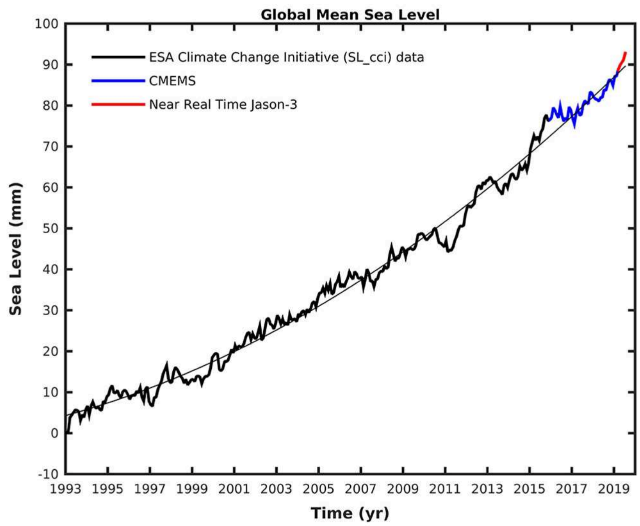

FIGURE 4 | Altimetry-based global mean sea level from January 1993 to February 2019. The black thin solid line is a quadratic function fitted to the data.

UNANSWERED SCIENTIFIC QUESTIONS AND NEW CHALLENGES IN TERMS OF GMSL MONITORING

To maintain the quality of the altimetry-based sea level record, sustained and ever more accurate observations from space are required. A longer sea level record with increased accuracy (fulfilling the GCOS requirements, GCOS, 2011) will allow addressing unanswered science questions such as: "Does the recently recorded acceleration of sea level rise represent a long-term shift toward a new climate regime? To what amount and over what time scale will potentially abrupt changes in the ice-sheet contributions affect the global sea level? How much heat has already reached the deep ocean? Can we constrain the Earth's energy imbalance and its temporal variations with improved global mean sea level observations? Is the regional variability in sea level only due to internal climate variability or can we already detect the fingerprint of anthropogenic forcing? When should the anthropogenic signal emerge out of the natural variability? Finally, which sectors of the global coastline will be affected first and at the greatest societal cost?" (Cazenave et al., 2019).

At the time of writing, 6 altimetry missions are in orbit (not counting the Chinese missions): Jason-2, Jason-3, SARAL/AltiKa, CryoSat-2, Sentinel-3A, and Sentinel-3B. Two of them (Jason-2 and SARAL/Altika) have been recently placed in non-repeat orbits, similar to the Cryosat-2 mission. However, not all satellites are included when estimating the global mean sea level. For example, NOAA, CU and GSFC only consider the reference missions, and C3S use two satellites (Jason-3 and Sentinel 3A) to extend the CCI time series. In the near future (2020), Sentinel 6 (Jason CS) will be placed on the same orbit as the TOPEX/Poseidon-Jason series. The SWOT mission based on interferometric altimetry technology, to be launched in 2021, will potentially also contribute to the global mean sea level monitoring. The scientific community universally supports the extension of the CryoSat-2 mission beyond 2019. On a longer time frame, the continuation of the radar altimetry record is less clear. Although the Jason and Sentinel satellite series are expected to provide essential sea level measurements over the coming decades for the mid-latitudes, in the Polar Regions—north and south of 82°, which includes the rapidly changing Arctic Ocean—a Polar orbiting cryosphere and ocean observing topography mission is as yet unsecured.

STERIC SEA LEVEL

Variations in steric sea level (i.e., due to ocean volume changes that result from density changes linked to temperature and salinity fluctuations) contribute significantly to sea level changes. Although satellite altimeters can measure total sea level change, they are unable to measure steric variability directly. Instead, *in situ* hydrographic measurements remain critical for sampling the subsurface of the ocean and determining the steric component of the total sea level change measured by satellite altimeters. During most of the Twentieth century, this involved temperature and salinity measurements collected by fixed-point moorings, oceanographic cruises and commercial ships. These data, however, suffer from serious sampling limitations that inhibit the understanding of steric sea level variability. The sampling in space is irregular—tied to ship tracks and fixed buoy locations—and the sampling in time is sporadic and seasonally biased. These issues are exacerbated as the record is extended further into the past, with logistically inaccessible and deeper parts of the ocean particularly undersampled. Furthermore, there is a northern hemisphere and seasonal sampling bias (most data collected during the summer), and remote areas of the global

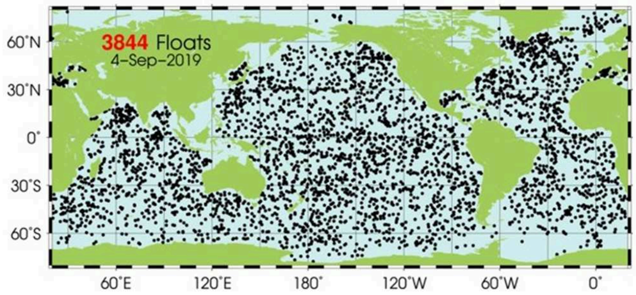

FIGURE 5 | Coverage of the global ocean by Argo floats on 04 September 2019.

ocean are poorly covered throughout the record and at all depths, with the Southern Ocean one of the gravest cases in terms of data coverage.

During the 1990s, the sampling situation improved significantly with the World Ocean Circulation Experiment (WOCE) project, an international initiative to develop surface and subsurface observing systems that complement satellite-measured sea surface height and sea surface temperature. From this project, a profiling float that could provide measurements of the subsurface of the ocean was developed. This eventually led to the installation of a global array of profiling floats, named Argo, with the primary motivation of assessing climate variability and change, including GMSL change due to steric variations (Roemmich et al., 2012, Riser et al., 2016). The first Argo floats were deployed in 1999, and the global network has included more than 3000 floats since 2007. That number now approaches 4,000 (**Figure 5**) with 25 national Argo programs around the globe contributing instruments and their deployment. With the data provided by the global array of Argo floats, the steric-related GMSL change has been estimated to be $\sim$1.31 $\pm$ 0.5 mm/year (WCRP Global Sea Level Budget Group, 2018) from 2005 to 2015, and a regional map of steric sea level change can be computed with comparable spatial variability to the altimeter-derived trend map over the same time period.

Despite the significant advances that have been made as a result of the Argo sampling program, observational needs remain with respect to improving our understanding of steric sea level change. The most prominently used Argo floats sample only to a depth of 2,000 m, limiting our understanding of the changes that may be occurring at depth layers below. Such changes would be reflected in the total sea level observations from satellite altimeters, which creates a gap in sea level budget calculations that rely on Argo for the steric contribution. Recent advances in profiling float and sensor technologies have led to the development of profiling floats that can sample to depths of 6,000 m (Zilberman, 2017). Regional pilot arrays are already in place in the Southwest Pacific Basin, South Australian Basin, Australian Antarctic Basin, and North Atlantic Ocean, and it is critical that a transition to full-depth global ocean observation continues to occur over the coming years. Additionally, even with the dramatic improvement in sampling with Argo profiling floats, there are still areas of the ocean that are undersampled, with marginal seas, shallow shelf areas, and seasonally ice-covered oceans among the most notable and scientifically important of these areas (Von Schuckmann et al., 2016). During early stages of Argo, the decision was made to avoid deployments in many marginal seas due to the risk of premature loss of floats and potentially problematic political issues. Since then, efforts have been made to encourage deployments in such areas, but as seen in **Figure 5**, areas like the Southeast Asian Seas (SEAS) remain very poorly covered. Variability in the SEAS region can have a substantial impact on global sea level and on heat storage on interannual timescales, making them critical to observe. Finally, coverage in areas poleward of 60 degrees North and South remains poor due to low deployment and high rates of attrition associated with the presence of sea ice floes that can damage the floats. Technological advances have been made that allow for ice avoidance of the floats, with increased lifetimes shown for these adapted floats. Increasing the deployment of ice-adapted floats would provide an improved understanding of sea level change at both global and regional scales.

MASS CONTRIBUTIONS

Mass changes and redistributions in the Earth system, notably redistribution of water (in its liquid, solid, or gaseous state), can be observed through their gravitational effect by satellite gravimetry missions. GRACE was a joint mission by NASA and DLR (the German Aerospace Center) which operated from 2002 to 2017. The mission concept built on the sensitivity of the orbits of low Earth orbiting satellites to the spatial details of the Earth's gravitational field. GRACE consisted of two satellites following each other in a distance of 200 km in a near-polar orbit. Variations in the distance between the two satellites, which are related to variations in the gravitational attraction of the Earth's mass, were measured by a K-band microwave ranging system with micrometer precision. A GPS tracking system for orbit determination, star cameras used for attitude determination and control and a 3D accelerometer for the measurement of non-gravitational accelerations were among the instruments completing the system. Based on the measurements, the global gravity field was solved for, typically on a monthly basis. The temporal variations of the monthly gravity field solutions were then analyzed to infer temporal changes in the mass of elements in the Earth system. GRACE is now followed by the GRACE-Follow-On (GRACE-FO) mission launched in May 2018 (https://gracefo.jpl.nasa.gov, https://www.gfz-potsdam.de/en/section/global-geomonitoring-and-gravity-field/projects/gravity-recovery-and-climate-experiment-follow-on-grace-fo-mission) with essentially the same mission configuration complemented by an even more precise laser ranging system between the twin satellites.

Satellite gravimetry is unique because it is directly sensitive to mass changes (rather than volume changes), including mass changes of the global ocean (Johnson and Chambers, 2013, Chen et al., 2013, Rietbroek et al., 2016). GRACE has enabled the "golden era" of sea level budget assessments where ocean mass change can be directly determined to complement

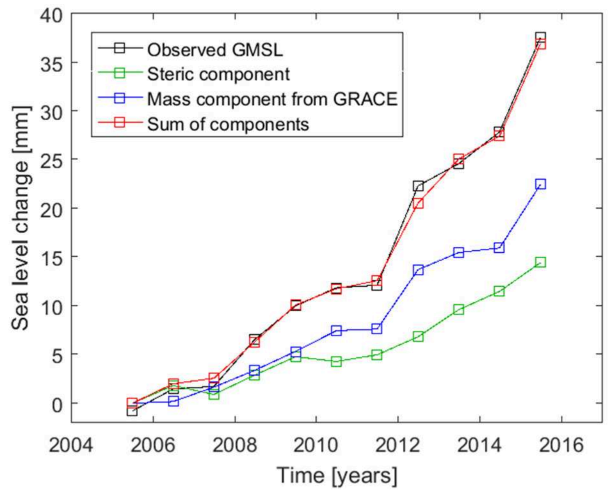

FIGURE 6 | The sea level budget over the golden era, using GRACE-based estimates of ocean mass change. The ensemble mean annual time series published by WCRP Global Sea Level Budget Group (2018) are shown.

the determination of volume change by altimetry and the determination of density change by the Argo sensor system. The WCRP study on global sea level budget (WCRP Global Sea Level Budget Group, 2018) provides a survey on recent GRACE-based ocean mass change studies and results (**Figure 6**).

Global mean ocean mass change may also be considered by assessing the individual contributions from mass changes of ice, snow, and water mass on land. Apart from the use of satellite gravimetry to determine these mass changes (discussed later), there are established approaches for such assessments for each land water/land ice storage component. The mass balance of the Antarctic and Greenland Ice Sheets can been estimated using a temporally continuous record of ice volume change measured by satellite altimetry missions since 1992, combined with an estimate of the density at which these changes occurred (Wingham et al., 1998; Shepherd et al., 2012, 2018; McMillan et al., 2014; Sørensen et al., 2018). Alternatively, the difference between surface mass balance into the basin estimated by a regional climate model (snow accumulation minus ablation), satellite observations of ice discharge out of the basin measured using InSAR or optical satellite data, and an estimate of the ice thickness across a flux gate, can be used to compute mass balance using the Input Output Method (IOM) (Mouginot et al., 2014). Mass changes of the world's mountain glaciers and ice caps have been estimated from the spatial extrapolation of field observations that are based on the direct or glaciological method for selected glaciers globally (e.g., Dyurgerov and Meier, 1997; Kaser et al., 2006) or later in combination with measurements based on the geodetic method, i.e., differencing of DEMs from at least two points in time (Cogley, 2009). More recently, the direct measurements have been used in conjunction with global-scale glacier modeling to infer their contribution forward (e.g., Radic and Hock, 2011) and backward in time (e.g., Marzeion et al., 2012). Another global-scale assessment of glacier mass change over the 2003–2009 period by Gardner et al. (2013) combined results from the glaciological method with trends in elevation derived from ICESat and gravimetric information from GRACE. Changes of the global continental water storage (including snow cover) at decadal (due mainly to groundwater depletion and man-made reservoirs) and seasonal scales have been assessed from global hydrological modeling (Döll et al., 2014a,b; Wada et al., 2017; Scanlon et al., 2018). In global hydrological modeling, a multitude of data including storage capacities of man-made reservoirs and the area of irrigated cropland are taken into account.

Satellite gravimetry has not only enabled the estimation of ocean mass change itself but has also added a powerful means of assessing its continental sources. GRACE has become instrumental in recording ice sheet mass change (Velicogna and Wahr, 2006, Horwath and Dietrich, 2009), in validating global hydrological modeling results (Döll et al., 2014a; Scanlon et al., 2018), and also in estimating mass losses of the world's glaciers and ice caps (Luthcke et al., 2008, Jacob et al., 2012, Gardner et al., 2013). By weighing mass changes in the Earth system due to whatever contributory process in an integrative, globally consistent way, satellite gravimetry has become the overarching technique for assessing the ocean mass budget.

Current limitations of satellite gravimetry can be summarized in four categories: (a) the limited temporal coverage, (b) the limited spatial resolution, (c) the problem of separating superimposed signals of mass change, including the GIA effects, and (d) the insensitivity to mass redistributions of spherical harmonic degree one (the so-called geocenter motion). These limitations directly translate into observational requirements for the future and will be discussed in the following.

(a) GRACE, originally designed for a 5-year lifetime, operated from 2002 through 2017, with some degradation of instruments and data recovery in the late years of the mission. Fortunately, GRACE-FO was launched in 2018, so that only a moderate gap occurred between the two missions. Since both missions determine the global gravity field in an absolute sense, no inter-mission calibration issues are expected. However, a long-term commitment to satellite gravimetry missions as a core element of Earth observation is not yet established by any organization. An essential observational requirement therefore consists in the continuation and operationalization of satellite gravimetry missions, following the example of, and complementing, satellite altimetry missions or meteorological missions. Recently, the National Research Council of the United States National Academies of Sciences, Engineering, and Medicine published the Decadal Strategy for Earth Observation from Space [Decadal Survey, NRC (National Research Council, The National Academies of Sciences, Engineering, and Medicine), 2018], where mass change was identified as one of the top 5 observables to be implemented by future US Earth observation missions in order to ensure continuity and enable long-term mass budget analyses of the Earth system.
(b) The attenuation of gravity field signals of small spatial scale at satellite height causes a decreasing sensitivity of satellite gravimetry to small spatial scales. In other words, the

spatial resolution of GRACE-based mass change inferences is coarse, unless the inferences are guided by additional a-priori information. The signal-to-noise ratio of GRACE-based mass changes decreases to less than one for spatial scales smaller than 200–500 km, depending on signal strength, time scale, and latitude. In addition, the GRACE (and GRACE-FO) orbital geometry in conjunction with deficiencies in modeling short-term mass variations induces distinctly anisotropic error characteristics reflected in north-south striping of unregularized solutions. The limits in spatial resolution lead to so-called leakage effects in attributing observed gravity field changes to the geographic location of the underlying mass changes. For the example of ocean mass budget applications, leakage effects manifest themselves in the difficulty of attributing an increase of gravitational attraction in the vicinity of coastlines to either regional ocean mass increase or regional continental water/ice mass increase, that is, to either a positive or a negative contribution to the ocean mass budget. The limited spatial resolution also prevents the detection of regional patterns of ocean mass change in a spatial resolution comparable to that of altimetry results and steric results.

New mission concepts with improved instrumentation and different satellite orbit constellations as well as improved modeling of background signals and improved processing strategies are means of increasing the spatial resolution of satellite gravimetry. In a community effort, Pail et al. (2015a,b) identified threshold and target scenarios for future satellite gravity missions, including the consideration of oceanographic and ocean mass change requirements. To meet these demands, currently several concepts for Next-Generation Gravity Missions (NGGMs) are under investigation and discussion. These concepts are usually based on high-precision inter-satellite ranging observations but differ in the set-up of the satellite constellation and the resulting observation geometry. In 2013 the mission concept called "e.motion" was proposed in response to ESA's Earth Explorer (EE) Call 8 (Panet et al., 2013). It was based on a pair of low-flying satellites in a so-called pendulum orbit, where the trailing satellite performs a relative pendulum motion behind the leading one. As another promising constellation, double-pairs in Bender configuration (Bender et al., 2008) consist of two GRACE/GRACE-FO-like pairs, where one pair flies in a (near-)polar orbit and the other one in an inclined orbit of 60° to 70°. This configuration significantly reduces the typical striping error patterns of GRACE and GRACE-FO temporal gravity solutions (Wiese and Visser, 2011; Daras and Pail, 2017). The EE9 proposal e.motion[2] (Gruber et al., 2015) was based on the idea of a Bender double pair. Another promising constellation is high-precision tracking between high or medium orbiting and low orbiting satellites (Hauk et al., 2017). The observation geometry, which is mainly in radial direction, results in a significant reduction of striping effects. It was the basis for the gravity mission proposal called "MOBILE" in response to the ESA EE Call 10 (Hauk and Pail, 2019).

(c) While the horizontal resolution of satellite gravimetry can be improved by refinement and extension of mission concepts, the inability of gravimetry to separate vertically superimposed signals of mass changes is a mathematical fact. While the separation of atmospheric mass changes is routinely conducted by use of atmospheric modeling, the separation of mass redistribution in the Earth's interior due to GIA from long-term redistribution of water and ice masses on the Earth surface constitutes a major source of uncertainty for GRACE-based ocean mass changes as well as GRACE-based mass contributions from the Antarctic Ice Sheet. The common way of accounting for GIA is to use geophysical GIA modeling results, which in turn rely on assumptions on glaciation history and Earth rheology (Spada, 2017; Whitehouse, 2018). The difference between global ocean mass change obtained when applying different global GIA models is on the order of 0.2 mm/year mean sea level (e.g., Blazquez et al., 2018). An additional complication arises from the fact that Antarctic ice sheet applications of GRACE have used regional GIA models, which are different from, and inconsistent with, global GIA models because global GIA models are considered incompatible with regional geological evidence on Antarctic glacial history (Ivins et al., 2013). Apart from improving geophysical GIA modeling by using the growing body of geological and geodetic constraints on sea level and glaciation history and by accounting for lateral variations of Earth rheology and non-Maxwell rheologies, it appears that geodetic observations of GIA, in particular GNSS observations of Earth surface deformations in Antarctica and Greenland, are a critical observational requirement for constraining ocean mass change and the ocean mass budget (King et al., 2010, Groh et al., 2012, Khan et al., 2016, Barletta et al., 2018). Satellite remote sensing by synthetic aperture radar has the potential of adding complementary, spatially extended information to the pointwise GNSS measurements (Auriac et al., 2013, Yan et al., 2016). Any development to observe bedrock deformations below ice sheets with a millimeter-per-year precision would fill crucial gaps in Antarctic GIA observation.

(d) Satellite gravimetry missions are insensitive to the largest spatial scale of water and ice mass redistribution, namely to the spherical harmonic components of degree one. Roughly speaking, degree-one patterns reflect a net mass exchanges between hemispheres, or in other words, a shift of the center of mass of the considered water and ice masses. The problem is directly linked to the determination of geocenter motion and thereby to the realization of the global terrestrial reference system origin and of the transformation between different origin definitions (Wu et al., 2012). Swenson et al. (2008) inferred degree-one components from a combination of GRACE-based gravity field variations with model-based assumptions on the water redistribution in the global ocean. This approach has been widely used with different modifications. However, with this approach the inferences on ocean mass change and ocean mass redistribution are inherently dependent on *a priori* assumptions about the same processes. The geodetic space techniques used to realize global terrestrial reference systems, in particular Satellite Laser Ranging, are capable of determining geocenter motion independently. It is of utmost importance to maintain and further develop the related global geodetic infrastructure and data analysis capacities. The International Association of Geodesy promotes this development by its Global Geodetic Observing System, and the United Nations (UN) have emphasized the importance by the resolution "Global Geodetic Reference Frame for Sustainable Development" (U. N. United Nations General Assembly, 2015; U. N. United Nations, 2016). The geodetic infrastructure related to the global reference frame realization forms the observational backbone for both the gravimetric determination of ocean mass changes and the geometric observation of sea level change by satellite altimetry, since the altimeter satellites' orbit determination crucially depends on reference frame realization.

The detailed assessment of the sources of ocean mass change in continental water and ice mass changes calls for further developments of their specific observation techniques and systems.

For the Greenland and Antarctic ice sheets, mass balance assessments will benefit from the ongoing and respective developments of satellite and airborne remote sensing, such as high-resolution and high-accuracy observations of surface elevation change from satellite altimeters with advanced resolution capability such as CryoSat-2, Sentinel-3, and ICESat-2, operational ice velocity mapping by imaging sensors such as Sentinel-1, Sentinel-2 and Landsat, ice thickness measurements by ground-penetrating radar to support assessments of discharge by ice flow, or firn radar measurements to support assessments of surface mass balance and firn processes. The mentioned techniques and missions need to be continued and further developed.

All estimates of glacier mass loss critically depend on the availability of a precise glacier inventory. Only with the availability of the Randolph Glacier Inventory in 2012 (Pfeffer et al., 2014) could the related global-scale calculations be performed with some certainty. Considering the rapid glacier shrinkage globally, a long-term strategy for monitoring global sea level has thus to ensure regular updates of the global glacier inventory (GCOS, 2011). Another obvious requirement concerns the information on glacier changes through time. Whereas field observations contribute direct measurements of annual or seasonal mass changes on the selected glaciers globally (Zemp et al., 2015), remote sensing data provide complementary information on glacier extent (from optical sensors), elevation changes (from repeat altimetry or Digital Elevation Model–DEM- differencing), and velocity to determine the mass flux for calving glaciers (from optical and microwave sensors). Well-established processing lines (Paul et al., 2015) provide these datasets from the fleet of currently available optical (e.g., Landsat, Sentinel-2, ASTER), microwave (e.g., Sentinel-1, ALOS PALSAR, TerraSAR-X/TanDEM-X), and altimetry sensors (e.g., ICESat-2, Cryosat-2), which need to be continued. Key technical issues to be addressed for improved geodetic mass balances are radar penetration for DEMs derived from microwave sensors (SRTM and TanDEM-X) and handling of data voids and artifacts over glaciers that are common in all DEMs (e.g., McNabb et al., 2019). There is also a requirement for the availability of DEMs, to update such DEMs frequently (e.g., every ten years), to provide them with a clear timestamp, and to improve constantly their quality and spatial resolution.

Estimation of land water storage changes (including snow) by global hydrological models can be improved in the future by data assimilation of multiple observational variables into global hydrological models (Döll et al., 2016). These observations include, in addition to *in situ* observations of streamflow, geodetic, and remote-sensing time series of total water storage anomalies from satellite gravimetry and GNSS, water table variations of surface water bodies and the extent of surface water bodies and snow. Of particular importance are more accurate global digital elevation models as well as remote-sensing-based stream flow estimates. Where access is possible, the water table elevation-streamflow relation could be determined first by an *in situ* measurement, which would allow translating radar altimetry measurements of water table elevations, ideally once per day, to streamflow time series.

The benefit from observational developments specific to the individual ocean mass sources discussed above will ultimately depend on the ability to consistently combine the observation systems for each individual element of the ocean mass budget and finally for the ocean mass budget and sea level budget as a whole. Pioneering examples include the combination of satellite altimetry, satellite gravimetry and GNSS to separate ice sheet mass changes and GIA (Riva et al., 2009; Gunter et al., 2014; Martín-Español et al., 2016; Sasgen et al., 2017) or integrating global geometric and gravimetric observations in global inversions for sea level changes and their contributions (Rietbroek et al., 2016).

INTEGRATION

By nature, the global mean sea level budget is an integrative topic. It combines different ECVs that are derived from totally independent observing systems. These include satellite altimetry, GRACE space gravimetry, *in situ* measurements of temperature and salinity from ships and Argo floats as well as outputs from various models.

As reported in recent publications, near closure of the sea level budget over the altimetry era indicates that no serious systematic errors currently affect these observing systems (at the level of 0.3 mm/year in terms of sea level trend equivalent). It also provides cross calibration of the systems.

Integrative analyses performed to examine closure of the sea level budget also inform on the level of uncertainty of each component, thus calling for additional research on adjacent topics. For example, uncertainty on the land water component derived from the budget analysis may question the quality of the meteorological forcing used to run the hydrological models. The level of closure also informs on missing components, e.g., deep ocean warming below 2,000 m not sampled by Argo, providing constraints on the current Earth energy imbalance (another important climate issue).

USER ENGAGEMENT

The primary users of the GMSL record and of the sea level budget are meteorological and climate organizations. The WMO now integrates the sea level ECV and the sea level budget in its yearly reports on the State of the Global Climate (WMO (World Climate Organization), 2019). The data sets for the GMSL already feed the "OBS4MIP" database of the WCRP. Data sets for the components of the sea level budget should also be included in OBS4MIP in the future. This will be most useful for CMIP (Climate Model Intercomparison Project) exercises, including coupled climate model validation. The IPCC (Intergovernmental Panel on Climate Change) reports are the ultimate users of this process.

In addition to these institutional users, public and private stakeholders are mostly interested in gaining information about GMSL changes. Although it is a slow process, sea level rise counts among the most ominous impacts of current climate change. It is one of the most pressing societal threats. Sea level rise at the coast results from several contributions: the global mean sea level rise, the superimposed regional variability, and the small-scale coastal processes. On the long term (several decades), the global mean rise will dominate the other factors. To assess present-day and future coastal risks (e.g., temporary and permanent flooding at the coast, shoreline retreat, etc.), national and regional authorities in charge of developing adaptation strategies to cope with climate change impacts, including sea level rise, represent a new category of end users that need to be regularly informed on the state of the climate and its future evolution. Novel procedures of communication toward the civil society, governmental organizations, and the private sector should be implemented so that the most up-to-date climate-related information, including the rate of sea level rise (present and future) and its causes (hence the sea level budget), can be regularly delivered outside the science community, in support of societal needs.

CONCLUSIONS AND RECOMMENDATIONS

To assess the global mean sea level budget, i.e., we need sustained observations with as global as possible coverage of sea level by satellite altimetry and of the steric and mass components from various space-based and *in situ* observing systems.

For *sea level*, we recommend:

- Continuity of the high-precision altimetry record beyond Sentinel-6/Jason-CS,
- Investigation of the possibility to modify the orbital characteristics of the reference missions in order to cover the Arctic Ocean,
- Maintain the level of quality of the historical past missions as high as possible (through regular data reprocessing) to ensure the homogeneity of the time series,
- Maintain the sea level measurements at high latitudes with the continuity of the CryoSat-2 mission.

For the *steric component*, priorities are (see also Meyssignac et al., 2019, this issue):

- Maintain support for Core Argo (www.argo.ucsd.edu, doi: 10.17882/42182),
- Implement Deep Argo,
- Perform regular subsurface temperature measurements (e.g., using dedicated Argo floats or other autonomous devices, and ship measurements) in areas not well-covered: marginal seas, high latitudes, boundary currents, and shallow areas and shelf regions,
- Perform/assure systematic calibration of Argo measurements using independent observing systems, notably the maintenance of CTD (conductivity/temperature/depth) shipboard measurements used for the quality control procedure for Argo measurements; assure development of these calibration values in-line with extensions of Argo (e.g., assure deep shipboard profiles for deep Argo).

For the *mass component*, recommendations include:

- Sustained measurements of ocean mass changes, of ice sheet and glaciers mass balances, and of land water storage changes from a GRACE-type mission with improved performances, especially in terms of spatial resolution,
- Sustained monitoring of land ice bodies using various remote sensing systems (InSAR, radar and optical imagery, standard radar as well as SAR/SARIN, and laser altimetry) and modeling,
- Improvement of global hydrological models, which requires, in particular, more accurate global digital elevation models as well as remote-sensing-based stream flow estimates.

In addition to observational requirements, we also recommend continuing modeling efforts for terms to consider in the global mean sea level budget but not yet easily accessible by observations. This includes improvement of GIA models.

Notwithstanding, reducing errors still affecting all terms of the sea level budget remains a major goal. Most recent studies of the global mean sea level budget find closure of the budget to about 0.2–0.3 mm/year in terms of trend, the attached uncertainty being on the order of 0.3 mm/year. This uncertainty level of 0.3 mm/year (of the same order of magnitude as some components; e.g., land water storage, GIA) looks to be a threshold that appears difficult to overcome. Moreover, this 0.3 mm/year uncertainty does not account for systematic errors affecting each term of the budget. For example, the GMSL trend (systematic) uncertainty is estimated to 0.3–0.4 mm/year (Legeais et al., 2018, Nerem et al., 2018). Errors of the wet tropospheric correction applied to the altimetry data and link between successive missions remain the largest contributors to the GMSL trend uncertainty (Ablain et al., 2019). Additional errors come from the Terrestrial Reference Frame in which the altimeter measurements are represented.

A space geodetic collocation experiment—GRASP (Geodetic Reference Antenna in SPace)—has been proposed to reduce some of these reference frame uncertainties by tying together the major geodetic techniques (GNSS, SLR, DORIS, and VLBI). More work is needed to understand the remaining systematic errors of each term of the budget and reduce them.

AUTHOR'S NOTE

In response to the OCEANOBS19 call for future observing systems of the ocean, the first three authors submitted community white paper abstracts dedicated to the sea level budget. They were further invited to group together to prepare a single merged article. This manuscript is the outcome of such a merging.

AUTHOR CONTRIBUTIONS

AC, BH, and MH wrote the manuscript, benefitting from input and improvement from all co-authors. All co-authors contributed to the paper.

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Satellite-Driven Estimates of Water Mass Formation and Their Spatio-Temporal Evolution

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We derive water mass transformation and formation rates using satellite-derived datasets of salinity, temperature and fluxes of heat and freshwater over the North Atlantic, North Pacific and Southern Ocean. The formation rates are expressed in three coordinate systems: (1) density, (2) temperature-salinity and (3) latitude-longitude. In the North Atlantic and North Pacific, peak formation occurs south of the western boundary current extensions during the winter months of the study period. In the Southern Ocean, wintertime peak formation occurs just north of the sub-Antarctic Front. The satellite-derived water mass properties and formation areas agree well with previous estimates from literature. The location of peak Mode Water formation varies slightly with time in all coordinate systems. We assess seasonal and inter-annual variability in all three basins from 2012 to 2014. We assess the impact of satellite uncertainties on final estimates of formation rates and areas with Monte-Carlo simulations. The simulations provide insights on the associated uncertainty of formation estimates. They also provide information on the geographic spread of the water mass formation area subject to the satellite errors. We find that the total uncertainty is dominated by the uncertainty in the sea surface salinity dataset. This stresses the need for frequent and increasingly accurate sea surface salinity data for reliable estimates of water mass formation rates and areas. Our study highlights the feasibility of providing satellite-based estimates of water mass formation rates and areas. The good spatio-temporal coverage of satellite data further adds to the utility of the approach.

Keywords: satellite, SMOS, water mass, water mass formation, sea surface salinity, mode water

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1. INTRODUCTION

Sea Surface Salinity (SSS) and Sea Surface Temperature (SST) are mostly set by heat and freshwater fluxes at the ocean-atmosphere interface. The variability of surface heat and freshwater fluxes in space and time causes spatio-temporally varying fields of SSS, SST and sea surface density (SSρ). Seawater consequently may exhibit a shift in density space causing a net gain or loss of water between different densities. The formation or destruction of a water mass with a specific density can be estimated from fluxes of heat and freshwater (e.g., Walin, 1982; Speer and Tziperman, 1992). This results in subduction or obduction of water through the base of the mixed layer.

A water mass is a body of water distinct from surrounding bodies of water in the ocean. Oceanographers identify and track these water masses in thermohaline coordinates using a temperature-salinity (θ–S) diagram. It was recently shown that θ–S diagrams can be obtained from satellite-derived SSS and SST (Sabia et al., 2014). Sabia et al. (2014) found a good agreement between satellite-derived results and the Array for Real-time Geostrophic Oceanography (Argo) *in-situ* Analysis System (ISAS) data. A slight freshening of satellite-derived results not captured by the gridded *in-situ* products was found to be positively correlated with rain events. They envisioned that this framework could be extended to study the temporal variability of water mass formation rates and areas. Based on the work by Sabia et al. (2014), we calculate the satellite-based formation rates of key water masses in the North Atlantic, North Pacific and Southern Ocean over the years 2012–2014. The formation rates are calculated as a function of fluxes of heat and freshwater according to Walin (1982) and Speer and Tziperman (1992). This framework ignores the impact of advection and entrainment.

Surface water masses are of critical importance as their properties are set by ocean-atmosphere interactions. The evolution of surface water masses to intermediate and deep water masses of the ocean has significant implications for climate studies. Particularly large surface water masses (in terms of volume) that exist throughout the ocean are known as Mode Waters. Three key Mode Waters have been characterised. Subtropical Mode Water (STMW) and Eastern STMW are located in the western and eastern parts of the subtropical gyres, respectively (Hanawa and Talley, 2001). Subpolar Mode Water (SPMW) occurs in the subpolar gyre of the North Atlantic and in the Southern Ocean. It is referred to as sub-Antarctic Mode Water (SAMW) in the latter case (McCartney, 1977; Hanawa and Talley, 2001).

The term Mode Water was first used by Worthington (1958) to refer to a particular water mass in the North Atlantic. He named this Mode Water the Eighteen Degree Water (EDW) because its temperature was centred at 18°C. This North Atlantic STMW is an example of a Mode Water associated with the subtropical gyre. Subsequent work has found counterparts to this Mode Water in all major basins in the northern and southern hemispheres (Masuzawa, 1969; McCartney, 1977; Gordon et al., 1987; Roemmich and Cornuelle, 1992; Provost et al., 1999).

In the present study, we aim at estimating the formation rates and areas for three of the most prominent Mode Waters: the EDW, the North Pacific STMW and the Southern Ocean SAMW. They are associated with the two strongest western boundary currents the Gulf Stream and the Kuroshio—and the sub-Antarctic Front, respectively. We use satellite data to track the formation of these water masses in θ–S space, density space and geographically.

The European Space Agency (ESA) pioneered the Soil Moisture and Ocean Salinity (SMOS) mission dedicated to better understanding the water cycle through accurate SSS measurements (Font et al., 2010). Since SMOS, the National Aeronautic and Space Administration (NASA) in conjunction with Comisión Nacional de Actividades Espaciales (CONAE—Argentina's Space Agency) launched Aquarius in 2011 with similar mission objectives to SMOS (Sen et al., 2006). NASA also launched the Soil Moisture Active Passive (SMAP) satellite in 2015, which remains a reliable source of satellite salinity datasets—especially since the loss of Aquarius in 2015 (Entekhabi et al., 2010). In the present study, we only consider satellite salinity data from SMOS.

SMOS uses a Microwave Interferometric Radiometre by Aperture Synthesis (MIRAS) operating at 1.4 GHz (L-Band). The acquired brightness temperatures (T_b) for a large number of incidence angles is a function of the dielectric properties of the sea surface. T_b is then converted to SSS using an iterative inversion scheme (Zine et al., 2008). Sun Glint, Galactic Radiation and Faraday Rotation all affect the T_b measurements obtained by SMOS (Font et al., 2010, 2012). They have to be taken into account to properly retrieve salinity from space. An average over 10–30 days of observations over an open ocean area of 100×100 or 200×200 km^2 with an accuracy of 0.1 PSU was aimed at in the SMOS mission requirements. To meet these objectives, the MIRAS instrument noise was reduced via an average over every grid cell and associated temporal window.

Previous estimates of water mass formation rates based on *in-situ* observations did not provide information about temporal variability. The synoptic and frequent coverage of satellites now enables us to study the spatio-temporal variability of water mass formation and its related uncertainty.

We describe the satellite and *in-situ* datasets and the methodology we use for estimating the water mass formation rates and their uncertainty in sections 2 and 3, respectively. We then present estimates of formation rates and their seasonal variability in section 4. In sections 5 and 6 we analyse the propagation of uncertainty in the satellite data to the final formation rates with the help of Monte-Carlo simulations and study the respective importance of uncertainty in SSS and SST. We conclude in section 7, stressing the potential of this framework to study water masses from space.

2. DATASETS

For computing satellite-derived estimates of water mass formation we use SSS data taken from ESA's SMOS satellite (Font et al., 2010, 2012). We use a L3 Binned SMOS SSS product produced by the Barcelona Expert Centre computed through the use of a weighted averaging of filtered SMOS L2 SSS values (Boutin et al., 2012; BEC, 2018). Weighted averaging was done through the computation of a theoretical uncertainty of SSS at every grid point.

The Operational SST and Sea Ice Analysis (OSTIA) dataset results from the optimal interpolation of a blend of data from both microwave and infrared satellite instruments. In addition, OSTIA uses *in-situ* observations to achieve very high resolution (1/20°) SST fields over the global ocean (Donlon et al., 2012). **Figure 1** shows SMOS SSS and OSTIA SST global maps averaged over January 2012.

The Argo ISAS dataset provided gridded fields of temperature and salinity taken entirely from *in-situ* sources and spans the years from 2002 to 2015. Monthly data for salinity and

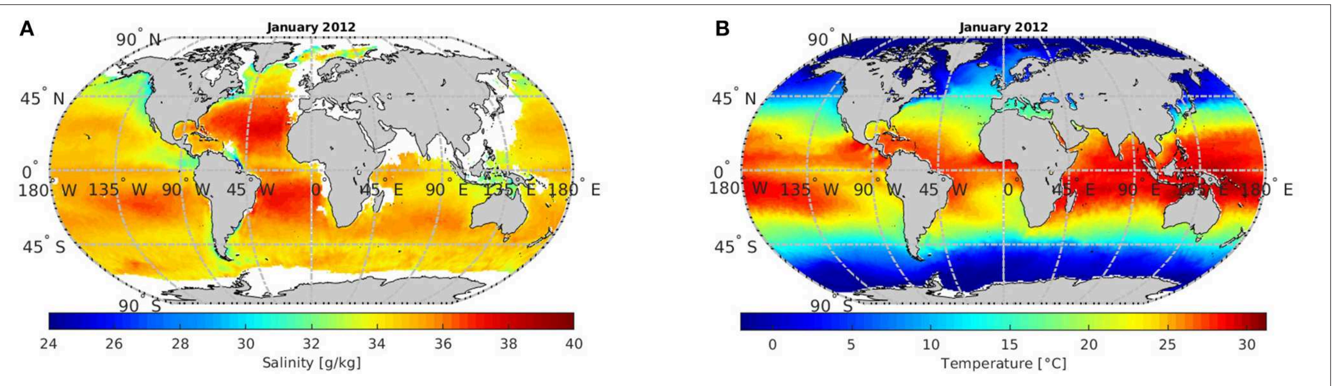

FIGURE 1 | SMOS global SSS map averaged over January 2012 **(A)** along with a global SST map derived from OSTIA **(B)**.

temperature were obtained to a depth of 1975 dbar in 58 levels (Gaillard et al., 2016; Kolodziejczyk et al., 2017). We use Argo ISAS datasets for SSS and SST as a reference by which we compare satellite-derived formation rates from SMOS SSS and OSTIA SST.

The National Oceanography Centre Southampton (NOCS) produced datasets for latent and sensible heat fluxes. Their version 2 heat flux dataset includes both the radiative and turbulent heat budgets of the surface ocean derived mainly from *in-situ* observations made by Voluntary Observing Ships using bulk formulas (Berry and Kent, 2009).

Evaporation and precipitation are taken from the Objectively Analysed Air-sea Fluxes (OAFlux) and the Climate Prediction Centre's morphing method (CMORPH) datasets, respectively. The National Oceanic and Atmospheric Administration (NOAA) produced both datasets (Joyce et al., 2004; Yu et al., 2008). The CMORPH dataset is a high spatio-temporal resolution dataset derived from a blend of satellite passive microwave and infrared scans (Joyce et al., 2004). OAFlux is an optimal blend of three atmospheric re-analyses and satellite retrievals from microwave, infrared, radiometre, scatterometre, and rainfall measurement missions.

For all datasets, we consider a temporal domain spanning 3 years from 2012 to 2014 in order to see seasonal and inter-annual variability in water mass formation. All data products have a monthly resolution and are remapped to a $1^\circ \times 1^\circ$ spatial resolution.

3. METHODOLOGY

We follow the method outlined by Speer and Tziperman (1992) in order to calculate water mass formation via air-sea fluxes of heat and freshwater.

3.1. Density-Flux, Transformation, and Formation

The transformation of water at a specific density is a function of the density flux at the surface of the ocean and it defines a cross-isopycnal volume flux. This can either be a movement of water to different densities—considering fixed isopycnals—or fluxes of heat and freshwater at the surface of the ocean causing a change in density. The following equations disregard advection and density changes that can occur due to vertical mixing effects at the base of the mixed layer.

The subsequent relation gives the density flux at the sea surface:

$$\mathbf{f(x,y,t)} = \frac{-\alpha H}{C_p} + \rho(0,T)\frac{\beta(W \cdot S)}{1-S} \tag{1}$$

Where,

$$\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial \mathbf{T}},\ \beta = \frac{1}{\rho}\frac{\partial \rho}{\partial \mathbf{S}} \tag{2}$$

Equation (2) shows the coefficients of thermal expansion (α) and haline contraction (β), respectively. $\rho(\mathbf{S}, \mathbf{T})$ is the density, T and S are SST and SSS, respectively. H is the air-sea heat flux and W is evaporation minus precipitation (**E–P**), better known as the freshwater flux. C_p is the specific heat capacity of water at 4,000 $JK^{-1}kg^{-1}$. The resulting surface density flux (**f(x,y,t)**) is then given in $kgm^{-2}s^{-1}$. Equation (1) can be expressed as **f(i,j,m)** when referring to latitudes, longitudes and months, respectively.

To derive a mathematical expression for water mass *formation* one must first define a *transformation* (i.e., the volume flux through a specific isopycnal). Formation would then be an accumulation or loss of water between two adjacent density surfaces. The volume flux through a specific density surface (transformation) is:

$$\overline{F(\rho)} = \frac{1}{\mathbf{T}\rho}\int dt \iint d\mathbf{A}\delta(\rho - \rho')f(x,y,t) \tag{3}$$

Note that the transformation F is a function of density and hence temperature and salinity. The over-bar on $\overline{F(\rho)}$ represents an average over T = 1 year and the outcrop density = 1 kgm^{-3}. As transformation is a volume flux, it is given in m^3s^{-1} or rather in Sverdrups (1 $Sv = 10^6 m^3 s^{-1}$). δ is the delta function being equal to 1 or 0 depending on whether one is within the area of the outcropping isopycnal in question ($\rho = \rho'$) or not ($\rho \neq \rho'$). If δ is 1 the equation proceeds to take the area integral of the surface density flux (**f(x,y,t)**) within the area of the outcropping isopycnal (ρ_θ).

The formation is then given by a rate of change of transformation given by:

$$\overline{M(\rho)} = -[\overline{F(\rho^2)} - \overline{F(\rho^1)}] \quad (4)$$

where the over-bar indicates an annual average. ρ^2 and ρ^1 represent two isopycnals with ρ located in between, such that $\rho^1 < \rho < \rho^2$. Formation then describes the convergence (positive M) or divergence (negative M) of transformation between the isopycnals ρ^1 and ρ^2.

At all grid points (*i, j*), we initially calculate f(i,j,m) (i.e., the monthly surface density flux). As the datasets are spatio-temporally discontinuous, calculations for transformation and formation are discretised. The integrals over area and time are replaced with a summation over the grid points (*i, j*) which fall into the area of the outcropping isopycnal or isotherm and isohaline. We achieve this by specifying bin widths of ρ, θ, and S at 1 kgm^{-3}, 0.5°C and 0.1 PSU, respectively. We also use a boxcar sampling function that is 1 within the outcropping area and 0 otherwise.

Every grid point (*i, j*) and every time step (when discretised) has a specific surface density flux associated with it. However, transformation and formation are only a function of density (or θ–S) and thus give no spatial information. The geographic pattern of regions of formation gives insight into the spatial and temporal variability of water masses in geographic space.

3.2. Formation in Geographic Space

The spatial pattern of formation was not considered in the study performed by Speer and Tziperman (1992), therefore, the following formulations are taken from Brambilla et al. (2008). They defined a spatial formulation of formation and transformation to study the Mode Waters in the subpolar gyre.

They calculated the formation at every time step, through the use of transformation at every time step:

$$M_m(\rho) = -[F(\rho^2) - F(\rho^1)] \quad (5)$$

and dividing this value by the region of the outcropping isopycnal in question $R(\rho)$,

$$S_{i,j,m}(\rho) = \frac{M_m(\rho)}{R_m(\rho)} \quad \forall i,j \;\; R_m(\rho) \quad (6)$$

they arrived at a formulation for the spatial representation of formation ($S_{i,j,m}(\rho)$), at every grid point and time step. A summation of this value over all time steps provides an annual average of $S_{i,j,m}(\rho)$.

$$\overline{S_{i,j}(\rho)} = \sum_{m=1}^{12} S_{i,j,m}(\rho) \quad (7)$$

Geographic representation of formation is practically done by defining a bounding box on a θ–S diagram. We define these bounding boxes to span 2°C and 0.5 PSU and centre around the visually identified point of peak formation. All positive formation pixels which lie within the box are then converted into geographic coordinates via (Equations 5–7).

3.3. Uncertainty Analysis—Methodology

SMOS and OSTIA, like any other remote sensing dataset, suffer from biases and inaccuracies due to intrinsic retrieval challenges (Font et al., 2010; Donlon et al., 2012). By perturbing the satellite SSS and SST data at every grid point, we can propagate these perturbations through to estimates of density flux, transformation and ultimately formation and compute statistics. This enables us to understand how uncertainties in the satellite datasets translate to uncertainties in the rates and location of water mass formation.

We use a Monte-Carlo simulation to introduce random perturbations in the satellite-derived datasets. We use a vector to store these random variables with a length equal to the number of Monte-Carlo realisations. We centre the random variables on the original SSS and SST values within a Gaussian distribution. They have a standard deviation close to the prescribed accuracy of the satellite SSS and SST datasets. 500 Monte-Carlo realisations are chosen for the subsequent analysis. The Monte-Carlo simulation takes the following form:

$$SSS, SST_{i,j,m}(n) = SSS, SST_{i,j,m} + \mathbf{x} \cdot s_{SSS,SST} \quad (8)$$

where **x** is a uniformly distributed random vector, *n* is the number of Monte-Carlo realisations and *s* is the prescribed standard deviation. *s* is chosen based on a comparison between SMOS/OSTIA and Argo ISAS. To show how respective errors in SSS and SST influence uncertainty in estimates of formation, we alternately eliminate their prescribed uncertainties.

4. RESULTS

Results for formation are computed over the North Atlantic (0°–44°N, 90.5°–0.5°W), North Pacific (5°S-59°N, 120°–240°E), and Southern Ocean (79.5°–40.5°S, with longitudes encircling the entire Southern Ocean). The respective regions are highlighted with black boxes in **Figure 2**. The area integral of the surface density flux results in the volume transport through each isopycnal (transformation) from 20 to 28 kgm^{-3}—the density range considered in the current study. Formation is then given by the net accumulation or loss of water between successive density surfaces. By partitioning the relative influences of SSS and SST on density, formation can also be visualised in θ–S space.

4.1. Surface Density Flux

The global surface density flux is calculated as an annual average over 2012 (**Figure 2**). The figure shows the tendency of water to lose or gain density based on processes and phenomena that act to vary the heat and freshwater fluxes over the surface of the ocean. The global maximum of surface density flux is located in the North Atlantic over the Gulf Stream at ∼45° to 80°W and 30° to 45°N. The density gain over the western boundary currents is associated with strong evaporation. In the equatorial regions, a density loss is caused either by heating through incoming solar radiation or by freshening through precipitation. This can be seen by the strongly negative values of surface density flux <–0.8 kgm^{-2} s^{-1} in the eastern Equatorial Pacific. The patterns over the rest of the global ocean remain consistent with these

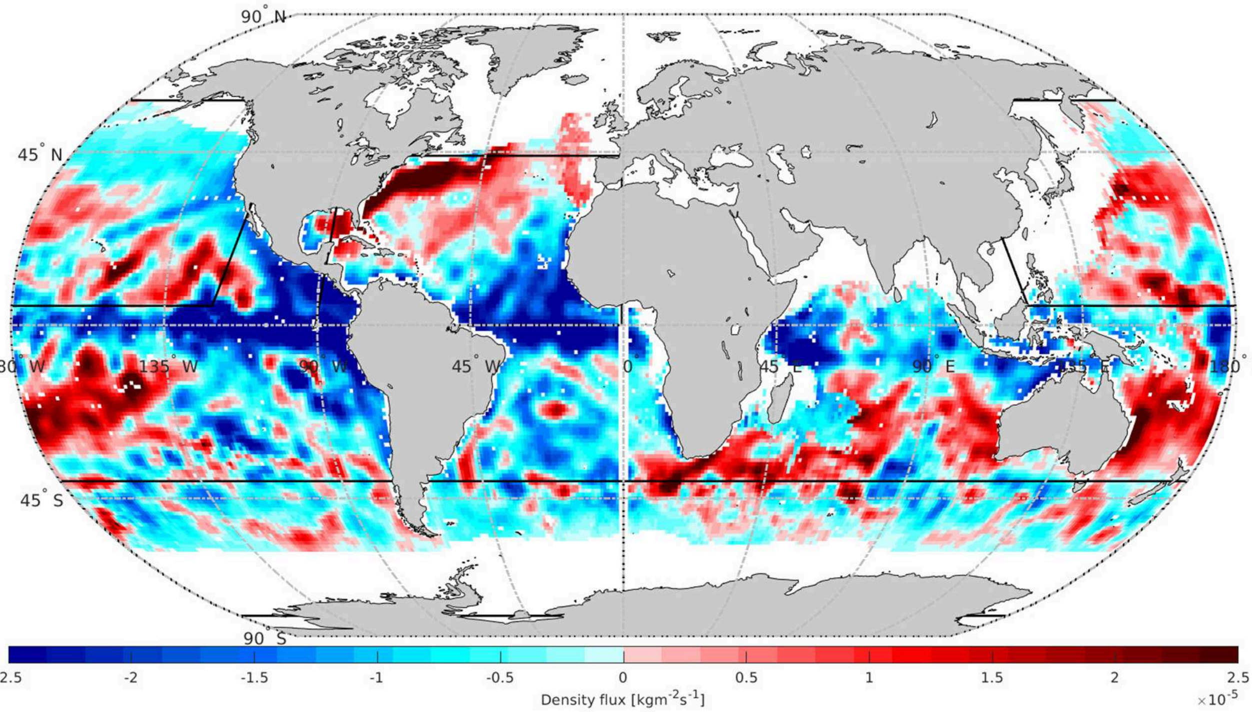

FIGURE 2 | Annual averaged surface density flux for the year 2012 calculated using SMOS SSS and OSTIA SST. The black boxes represent the boundaries defined for the North Atlantic (0°–44°N, 90.5°–0.5°W), the North Pacific (5°S–59°N, 120°–240°E) and the Southern Ocean (79.5°–40.5°S, with longitudes encircling the entire Southern Ocean). Missing density flux estimates (indicated in white) are related to issues of satellite salinity retrieval due to Radio Frequency Interference or signal contamination from land contiguity.

observations. The strongest density gain is most apparent at mid latitudes associated with boundary currents.

4.2. Formation in θ–S Space

By separating density into the relative contributions from SSS and SST it is possible to visualise formation in the θ–S bivariate plane. Results are shown over the winter months in 2012. Isopycnals are superimposed ranging from 16 to 30 kgm^{-3} (**Figure 3**). We consider a temperature and salinity range of 0–35°C and 27–39 PSU. This is sufficient to capture formation for the entire area of all basins studied. Looking at formation on a θ–S diagram allows for a greater degree of comparison with both literature and *in-situ* derived formation estimates. It also allows for a deeper diagnosis into the distribution and dynamics of formation estimated solely through satellite datasets. In **Figure 4**, the seasonal water mass formation evolution for the various satellite-driven inputs in the three basins is shown.

In the North Atlantic (**Figure 3A**), two distinct peaks of positive formation are visible from both the satellite and *in-situ* datasets. For Argo ISAS the extent of the ridge differs by 0.3 PSU and 1.5°C from SMOS-OSTIA. Both dataset combinations peak in formation within this ridge at ∼36.9 PSU and 20.5°C. The same ridge in θ–S space was associated with the properties of the Gulf Stream by Sabia et al. (2014). This matches the geographic location of the EDW (Worthington, 1958).

In the North Pacific, the peak formation based on SMOS-OSTIA is centred at 17°C and 35 PSU as shown in **Figure 3B**. Based on Argo ISAS, the peak formation is centered at the same salinity but the temperature is ∼3°C warmer. Looking at the seasonal distribution (**Figures 4e–h**), this particular water mass peaks in the autumn and winter months (OND-JFM) and matches the θ–S location of North Pacific STMW (Masuzawa, 1969).

McCartney (1977) defined two water masses in the Southern Ocean north of the sub-Antarctic front, close to the Drake Passage in the South Atlantic. He defined a warmer, saltier water mass at 15°C and 35 PSU and a colder, fresher water mass at 4°C and 34.2 PSU. The formation derived from Argo ISAS shows only a single peak at 7°C and 34 PSU. The formation derived from SMOS-OSTIA, on the other hand, captures two distinct water masses in the Southern Ocean. The first is slightly colder and fresher at 10°C and 34.4 PSU; the second is warmer and more saline at 12.5°C and 35.5 PSU. Peak formation in each season spans a specific θ–S range. These peaks are indicated by small black boxes in **Figures 5a–c** (see section 3.2). To compare the satellite-derived properties with literature estimates, we indicate the literature-based properties by yellow dots. Overall, there is a remarkable agreement between the satellite-derived peak formation θ–S ranges and the Mode Water properties from literature. Based on our defined peak formation properties, we can now map the formation peaks into geographic space (**Figures 5d–f**).

In the North Atlantic, peak winter formation occurs close to the subtropical gyre as shown in **Figure 5d**. This agrees well

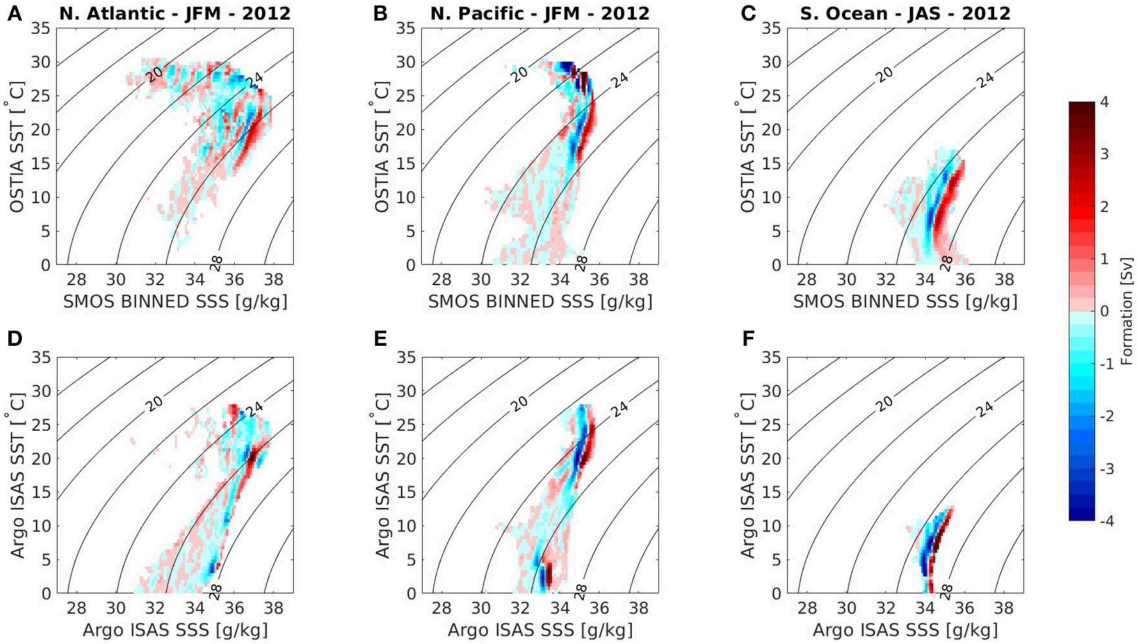

FIGURE 3 | Formation in θ–S space for the North Atlantic (left), North Pacific (middle) and Southern Ocean (right), derived from SMOS SSS and OSTIA SST **(A–C)** and Argo ISAS SSS and SST **(D–F)** averaged over the winter months in 2012.

with the literature-based formation region (yellow shading in **Figure 5d**; Worthington, 1958; Hanawa and Talley, 2001).

Recent work using data from a 2000 to 2015 Argo climatology has shown that the location of core EDW conservative temperature and absolute salinity contours lie eastward relative to our satellite-derived geographic location of peak winter formation in the North Atlantic (Worthington, 1958; Feucher et al., 2019). This discrepancy could be due to sensing of additional processes by the superior spatial coverage of satellites.

In the North Pacific, the satellite-derived Mode Water properties agree remarkably well with literature-based properties of the North Pacific STMW (**Figure 5b**; Masuzawa, 1969; Feucher et al., 2019). The geographic location of the formation peak also corresponds well with the qualitative estimates of the North Pacific STMW formation area from literature (Masuzawa, 1969; Hanawa and Suga, 1995).

The position of the Southern Ocean water mass (**Figure 5f**) fits with the account of McCartney (1977) who found the coldest and freshest water mass just west of the Drake Passage. The core temperatures and salinities of the colder SAMW from literature (yellow dot in **Figure 5c**) and peak winter satellite-derived formation in θ–S coordinates differ slightly, perhaps reflecting the sparse surface observations in the Southern Ocean and as such poor heat flux estimates for the region (Josey et al., 1999; Kubota et al., 2003; Dong et al., 2007). Accurate air-sea flux estimates are critical for the estimation of water mass formation, especially in the Southern Ocean. Cerovečki et al. (2011) recently compared air-sea flux estimates in the Southern Ocean from a variety of sources. They reduced biases in a reanalysis product using adjustments from the Southern Ocean State Estimate (SOSE). The bias reduction showed that SOSE is a possible source of high-resolution fields of air-sea fluxes that are needed for an accurate estimation of water mass formation in the Southern Ocean. **Figures 6–8** describe the inter-annual variability of seasonal formation in the North Atlantic, North Pacific and Southern Ocean. As in **Figure 5**, we mark the SSS and SST ranges of the peak formation of EDW, North Pacific STMW and SAMW during the autumn and winter months (black boxes) and compare them to the literature-based properties (yellow dots). In general, the satellite-derived formation peaks agree better with the literature-based water mass properties during the winter rather than autumn (Hanawa and Talley, 2001). The year 2013 represents the greatest agreement between literature properties of the EDW and satellite-derived peak water mass formation in both winter and autumn. The deviation between literature-based Mode Water properties and satellite-derived estimates for peak formation is greatest in 2014 in all three basins. For a better overview, we also present a comparison between the properties of satellite-derived formation peaks and the literature-based Mode Water properties in **Table 1**. **Figure 9** shows spatial patterns of formation derived from SSS and SST ranges defined for the North Atlantic formation peak in winter (JFM). **Figure 9** is the geographic equivalent to **Figure 6**. The geographic formation is seen to closely match literature in 2013, where spatial patterns of formation lie closer to the Gulf Stream (**Figure 9**; Worthington, 1958; Hanawa and Talley, 2001).

Satellite estimates—due to their superior coverage over *in-situ* datasets—represent an added value in understanding the variability of water masses in space and time, as compared to literature estimates.

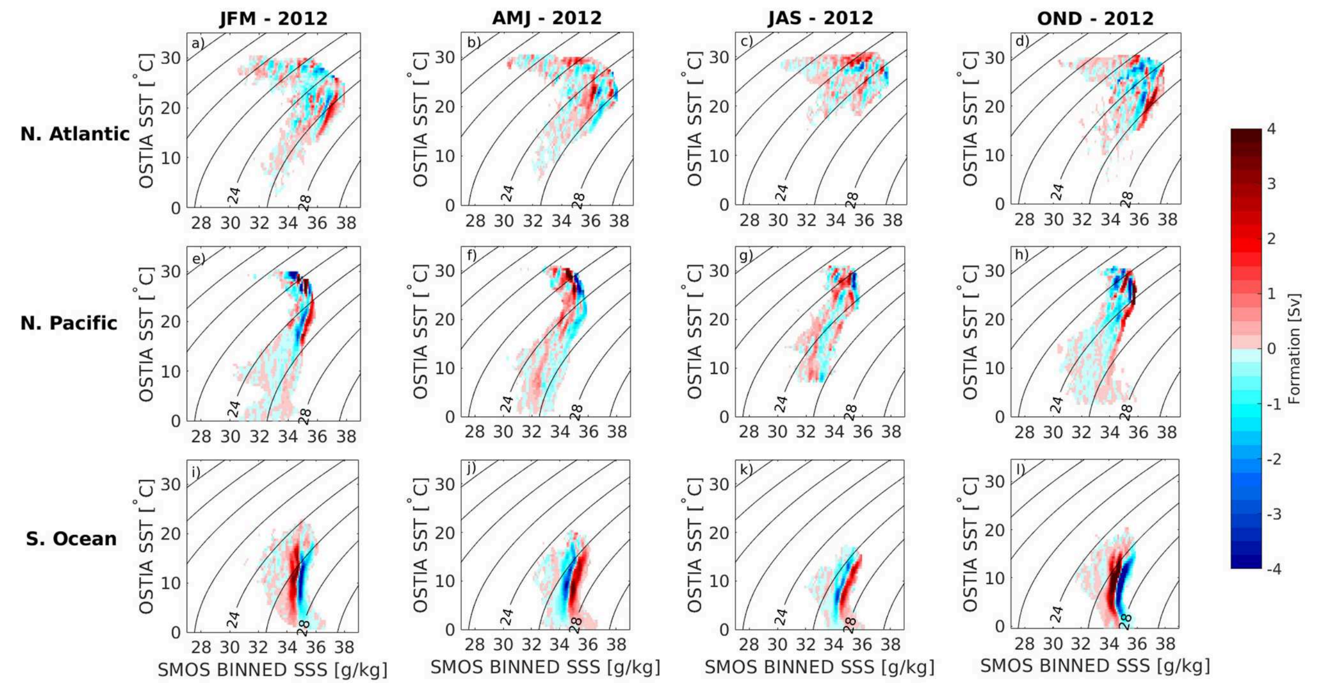

FIGURE 4 | Seasonal evolution of formation for the North Atlantic **(a–d)**, North Pacific **(e–h)**, and Southern Ocean **(i–l)**, averaged over winter (JFM), spring (AMJ), summer (JAS), and autumn (OND) of the year 2012.

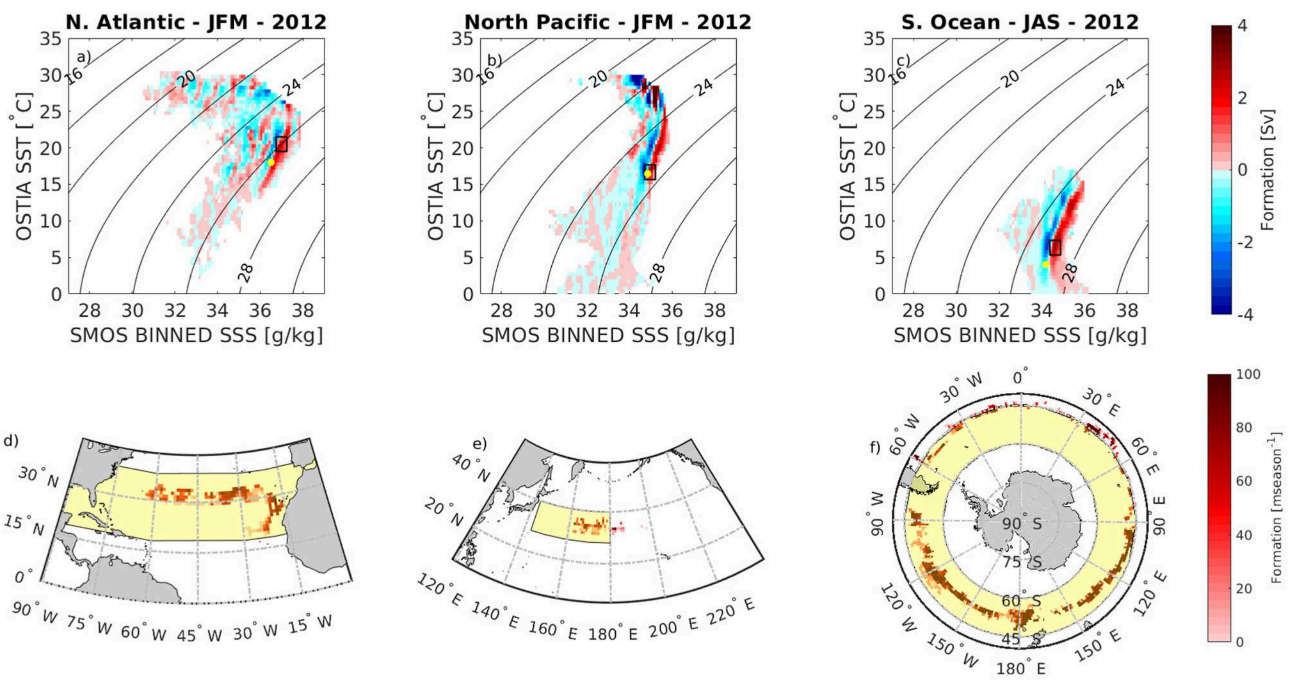

FIGURE 5 | Averaged formation over the winter season in the North Atlantic **(a)**, North Pacific **(b)** and Southern Ocean **(c)**. Yellow dots **(a–c)** indicate literature properties of Mode Water within the respective basins. Maps of positive water mass formation are shown in **(d–f)** with the approximate geographic literature locations shaded in yellow (Worthington, 1958; McCartney, 1977, 1982; Hanawa and Hoshino, 1988; Yasuda and Hanawa, 1997; Hanawa and Yoritaka, 2001).

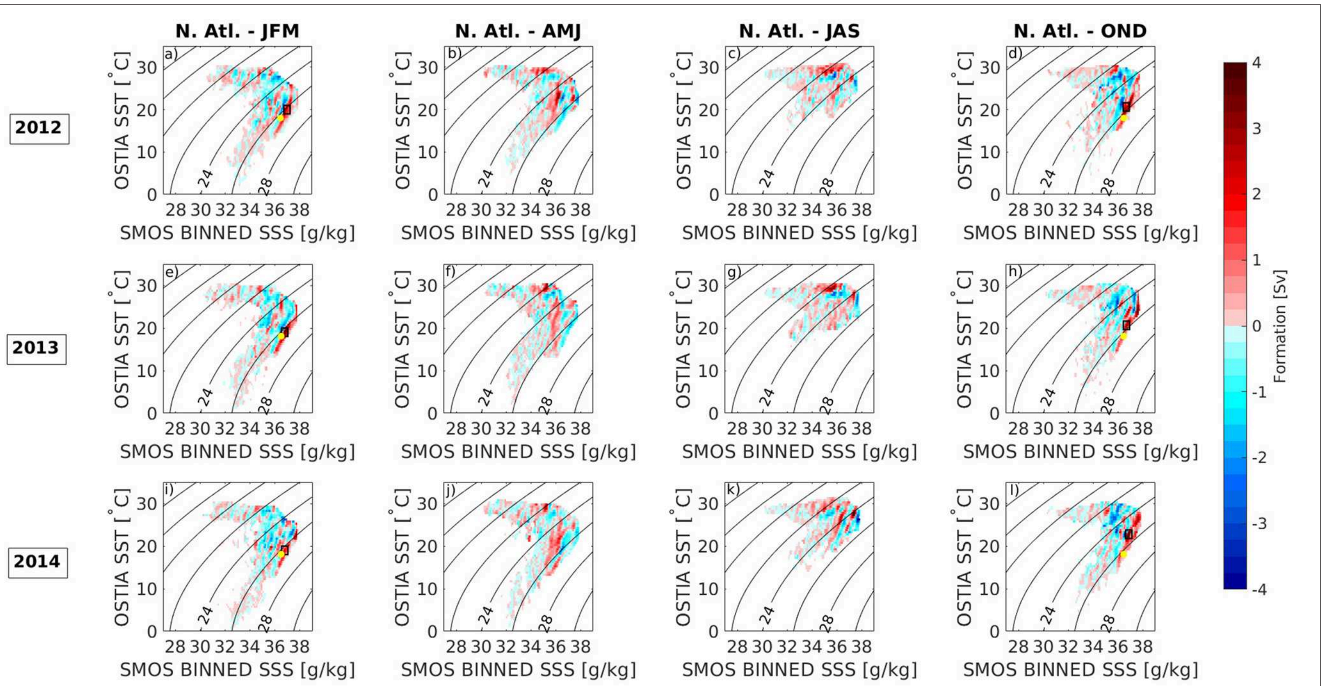

FIGURE 6 | Seasonal formation from the North Atlantic in θ–S space over the years 2012 **(a–d)**, 2013 **(e–h)**, and 2014 **(i–l)**. The four panels from left to right at each year indicate winter (JFM), spring (AMJ), summer (JAS), and autumn (OND), respectively. The yellow dots on the figures in the left and right most columns (JFM and OND) show the literature properties of the EDW (Worthington, 1958).

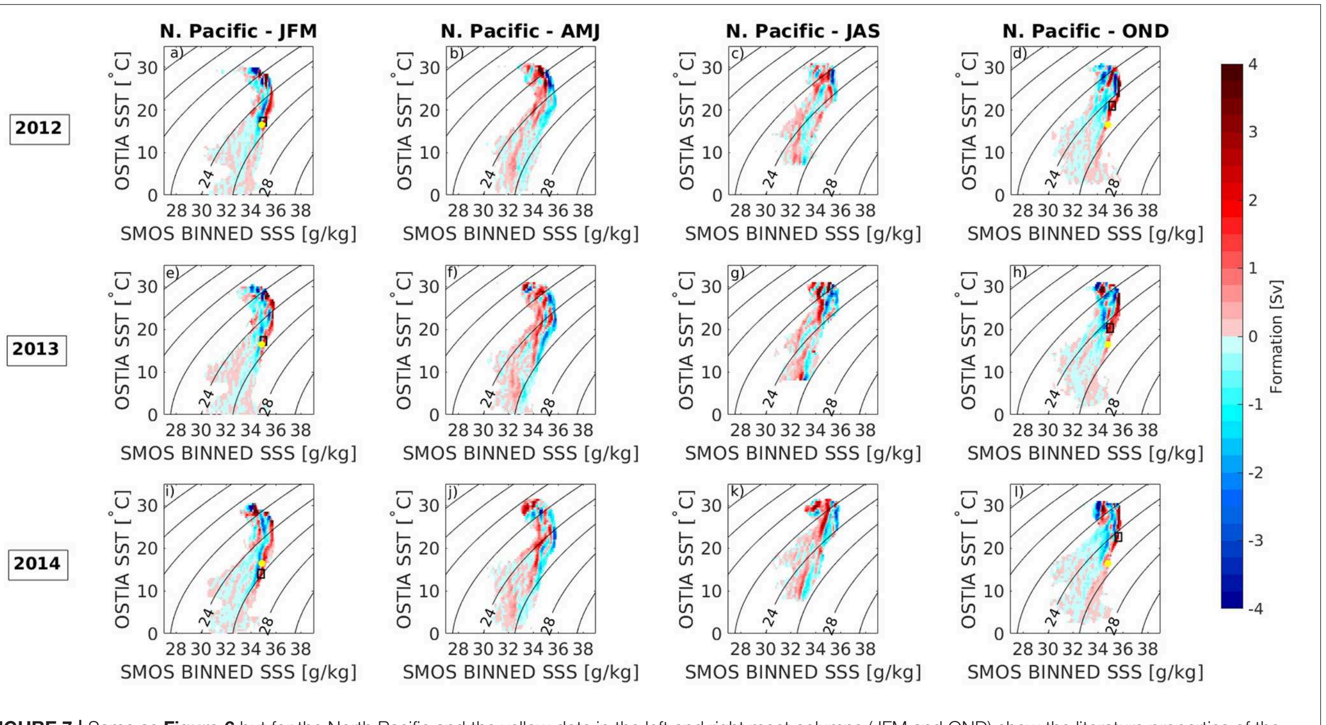

FIGURE 7 | Same as **Figure 6** but for the North Pacific and the yellow dots in the left and right most columns (JFM and OND) show the literature properties of the North Pacific STMW (Hanawa and Hoshino, 1988; Yasuda and Hanawa, 1997; Hanawa and Yoritaka, 2001).

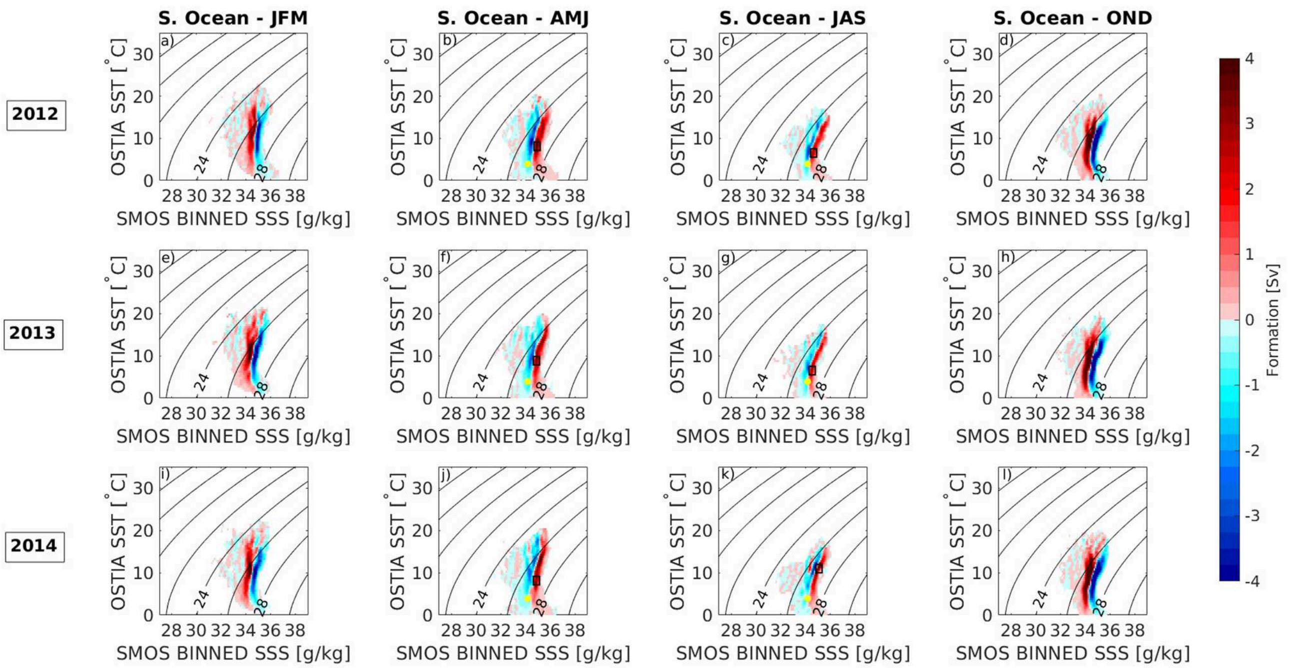

FIGURE 8 | Same as **Figure 6** but for the Southern Ocean and the yellow dots in the two centre columns (AMJ and JAS) show the literature properties of the SAMW (McCartney, 1977, 1982).

TABLE 1 | Characteristic temperatures, salinities, and densities of Mode Waters in the North Atlantic, North Pacific, and Southern Ocean found in literature using *in-situ* data.

Basin	Name	Source	θ (°C)	S (PSU)	ρ (kgm^{-3})
N. Atlantic	North Atlantic STMW (EDW)	Worthington, 1958; Talley and Raymer, 1982	18	36.5	26.5
		SMOS-OSTIA	19.5–21.5	36.8–37.2	25.58–26.42
N. Pacific	North Pacific STMW	Masuzawa, 1969; Hanawa and Hoshino, 1988; Yasuda and Hanawa, 1997; Hanawa and Yoritaka, 2001	16.5	34.85	25.2
		SMOS-OSTIA	15.5–17.5	34.8–35.2	25.12–25.89
S. Ocean	SAMW	McCartney, 1977	4	34.2	26.5
		SMOS-OSTIA	10–12	34.4–35	26.75–27.49

They are compared to estimated peak winter formation from SMOS-OSTIA.

5. UNCERTAINTY ANALYSIS–RESULTS

5.1. Uncertainty of Water Mass Formation in σ-Space

As a first step, we estimate the uncertainty of the satellite-derived formation rates in σ-space. We use the Monte-Carlo simulations to propagate the respective uncertainties in SSS and SST to the formation estimates as described in section 3.3. We perform the Monte-Carlo simulations for all three basins and for the years 2013 and 2014. The uncertainty is visualised by the error bars, which are placed at 0.1 kgm^{-3} intervals. We also include formation estimates based on Argo ISAS data for comparison.

The satellite-derived formation peaks are shifted towards lighter densities with respect to the Argo-based estimates (**Figure 10**). This may reflect the fact that satellite-based salinity estimates are influenced by rain events (Ma et al., 2015). In 2013, the North Atlantic (**Figure 10A**) experiences a peak in positive formation at 26 kgm^{-3}. However, in 2014 the closest peak of positive formation exists at 25.7 kgm^{-3}. Peak positive formation at 25.7 kgm^{-3} is overestimated with respect to literature—which places an approximate range of 3.6 and 5.6 Sv at the lower and higher ends, respectively (Kwon, 2004; Maze et al., 2009).

Masuzawa (1969) places the core density properties of the North Pacific STMW at 25.2 kgm^{-3}. This approximately

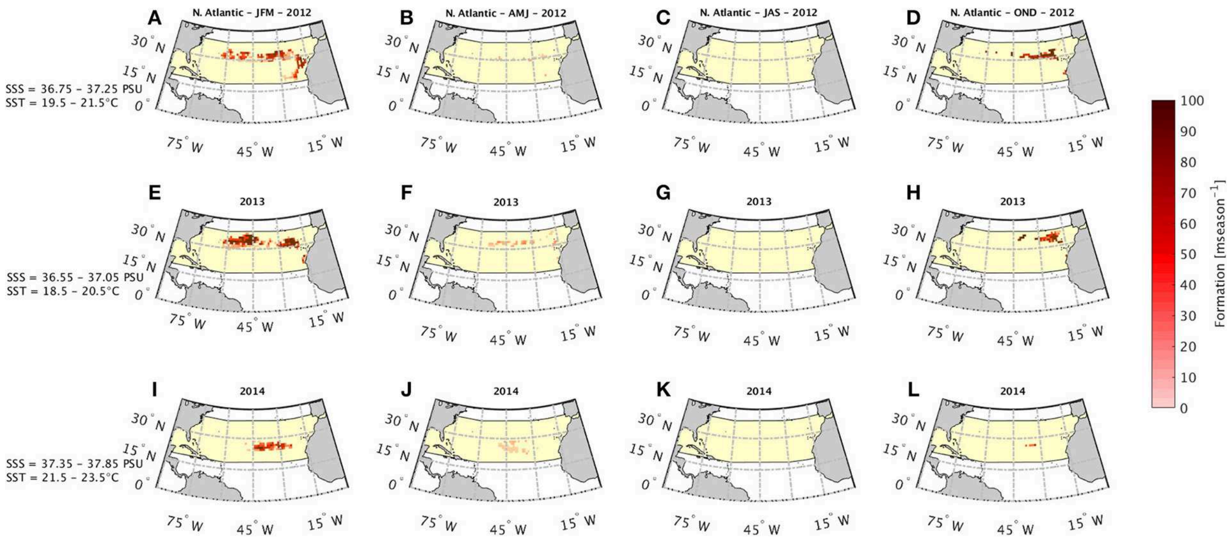

FIGURE 9 | The geographic distribution of the water mass formation peak in the North Atlantic for the years 2012 **(A–D)**, 2013 **(E–H)**, and 2014 **(I–L)**, and for the respective seasons winter (JFM), spring (AMJ), summer (JAS) and autumn (OND). The approximate geographic location of the EDW is shaded in yellow (Worthington, 1958; Hanawa and Talley, 2001).

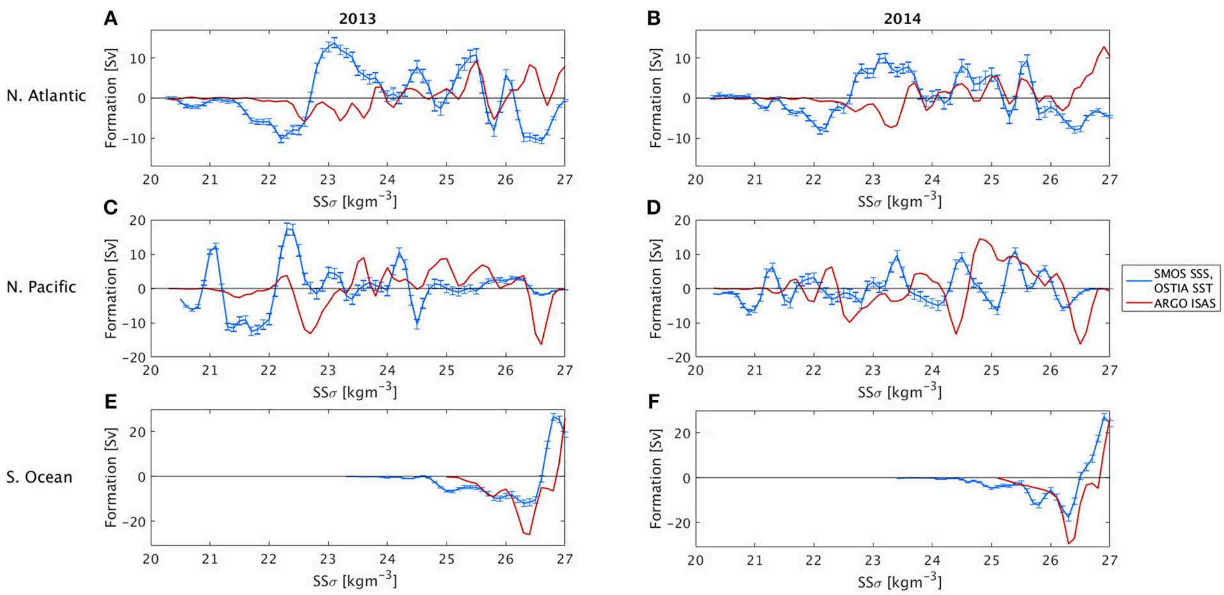

FIGURE 10 | Annually averaged formation with error bars in σ-space for the year 2013 (left column) and 2014 (right column) over the North Atlantic **(A,B)**, North Pacific **(C,D)**, and Southern Ocean **(E,F)**. The blue and red lines indicate formation in σ-space calculated using SMOS-OSTIA and Argo ISAS SSS and SST, respectively. Error bars indicate uncertainty over 500 Monte-Carlo realisations.

coincides with a peak in 2014 (**Figure 10D**) located at 25.3 kgm^{-3}. In 2013, there is less agreement with literature as the closest positive formation peak occurs at 24.9 kgm^{-3} (**Figure 10C**) (Masuzawa, 1969).

According to McCartney (1977) there exist a warm and cold SAMW due to the nature of the sub-Antarctic Front. The coldest SAMW has a core density of 27.1 kgm^{-3} which lies closer to the positive formation peak in 2014 (**Figure 10F**) rather than 2013 (**Figure 10E**).

5.2. Uncertainty of Water Mass Formation in θ–S and Geographic Space

Formation in θ–S space as a result of the 500 Monte-Carlo simulations is presented in **Figures 11a,b**. We then apply a bounding box to each formation peak for each specific Monte-Carlo realisation. The mean and standard deviation are calculated over the entire ensemble of formation realisations. Thereafter, we compute the respective geographic distribution for all θ–S diagrams (**Figures 11c,d**).

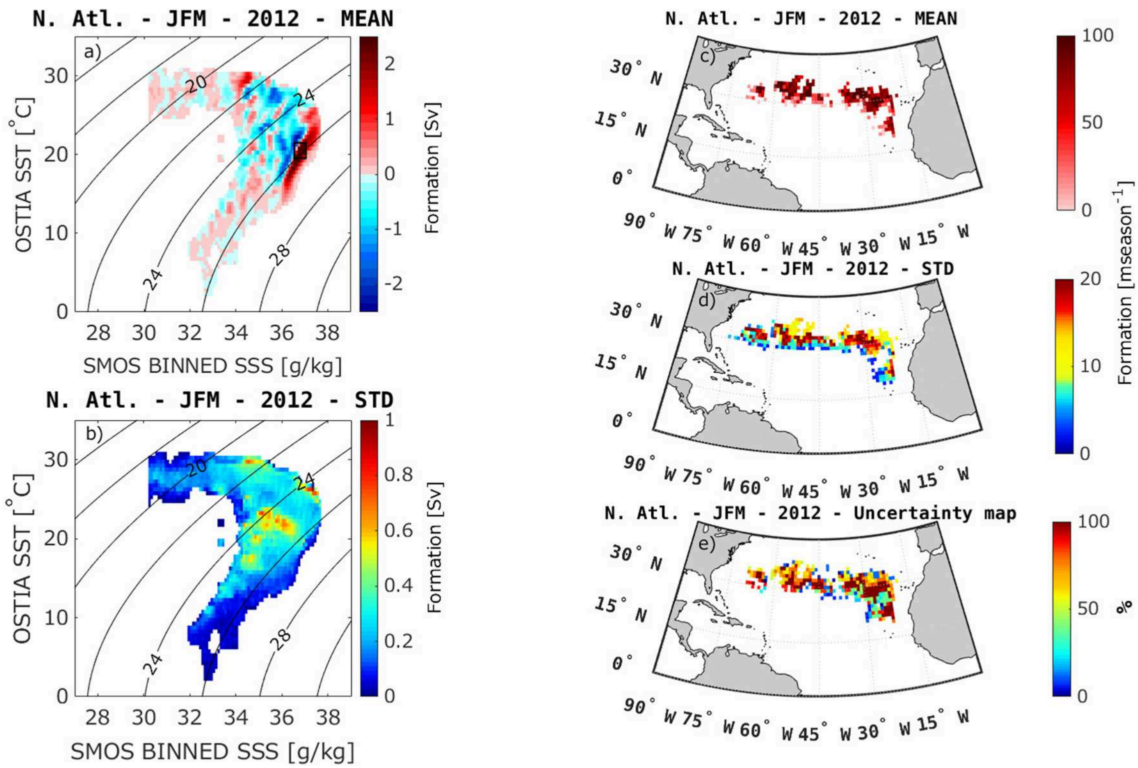

FIGURE 11 | Mean and standard deviation of formation averaged over the North Atlantic during winter (JFM) in 2012 using 500 Monte-Carlo realisations. Mean and standard deviation of formation in θ–S space **(a,b)** and geographic space **(c,d)** is shown along with the uncertainty in the geographic extent of formation **(e)**.

At every lat-lon point, we calculate the likelihood of formation occurrence as the percentage frequency at which positive formation occurs within the ensemble of geographic distributions (**Figure 11e**). **Figure 11d** represents the uncertainty in the formation estimates due to the uncertainty in the underlying satellite data. In **Figure 11e**, this uncertainty is translated into an uncertainty in the geographic distribution of a specific water mass.

Results show that after 500 Monte-Carlo simulations the winter mean formation peak centres at 37 PSU and 20°C. If the uncertainties in SMOS-OSTIA are not considered, the equivalent formation peak is shifted by 0.1 PSU and 0.5°C towards more saline and warmer waters, respectively (compare **Figure 5a**). These θ–S values are also further from the 36.5 PSU and 18°C found by Worthington (1958).

The geographic distribution agrees more with literature after a mean over 500 Monte-Carlo simulations. This results in a spread over a greater extent south of the Gulf Stream extension than in **Figure 5d** (Worthington, 1958; Hanawa and Talley, 2001; Maze et al., 2009).

6. SENSITIVITY ANALYSIS

In this section, we intend to assess the relative contributions of θ and S to uncertainties in water mass formation. To do this, we consider uncertainties in only one of the datasets at a time. We compare these partial uncertainty estimates in θ–S (**Figure 12**) and geographic space (**Figure 13**) to the estimates of total uncertainty.

When we consider only uncertainties in SST, the standard deviation of the Monte-Carlo ensemble is much smaller than the total standard deviation due to the combined uncertainties of SST and SSS (**Figures 12d,e**). Also, the mean after 500 Monte-Carlo simulations matches **Figure 5a** (i.e., assuming both SSS and SST to be perfectly known). When we consider only the uncertainties in SSS, the standard deviation of the Monte-Carlo ensemble closely resembles the total standard deviation (**Figures 12d,f**). The sensitivity experiment thus suggests that most of the uncertainty in the formation estimates can be attributed to uncertainties in SSS.

The extent of the formation area in geographic space is spread over a narrower latitudinal range when the uncertainties in SSS are ignored (**Figure 13h**). Therefore, we conclude that the uncertainties in SSS also dominate the uncertainties in geographic space—in terms of both the formation rate (**Figures 13d–f**) and the formation area (**Figures 13g–i**).

7. CONCLUSION

We calculate annual and seasonal water mass formation rates based on satellite SSS and SST in the North Atlantic, North Pacific and Southern Ocean for the years 2012 to 2014. The calculation is based on the variability of heat and freshwater fluxes (Walin, 1982; Speer and Tziperman, 1992). We further

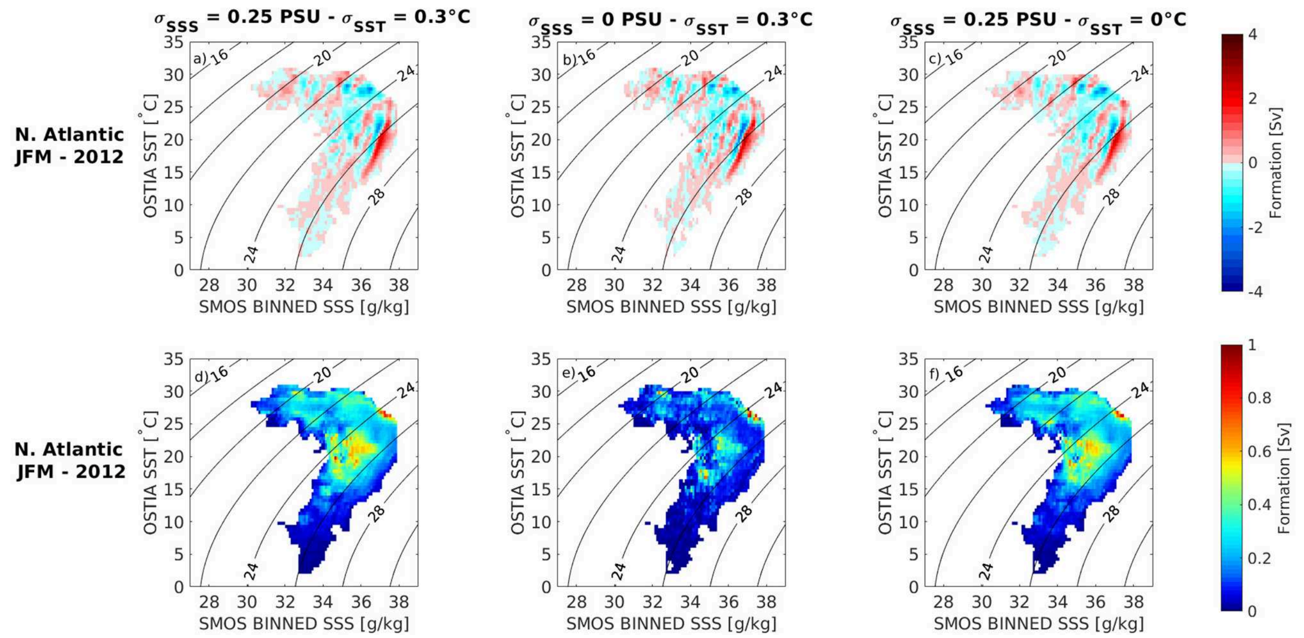

FIGURE 12 | Mean **(a–c)** and standard deviation **(d–f)** of formation in θ–S space during the winter months (JFM) in 2012 over the North Atlantic after 500 Monte-Carlo realisations. The Monte-Carlo simulation was run three times with uncertainties considered in both SMOS SSS and OSTIA SST (first column), only OSTIA SST (second column) and only SMOS SSS (last column).

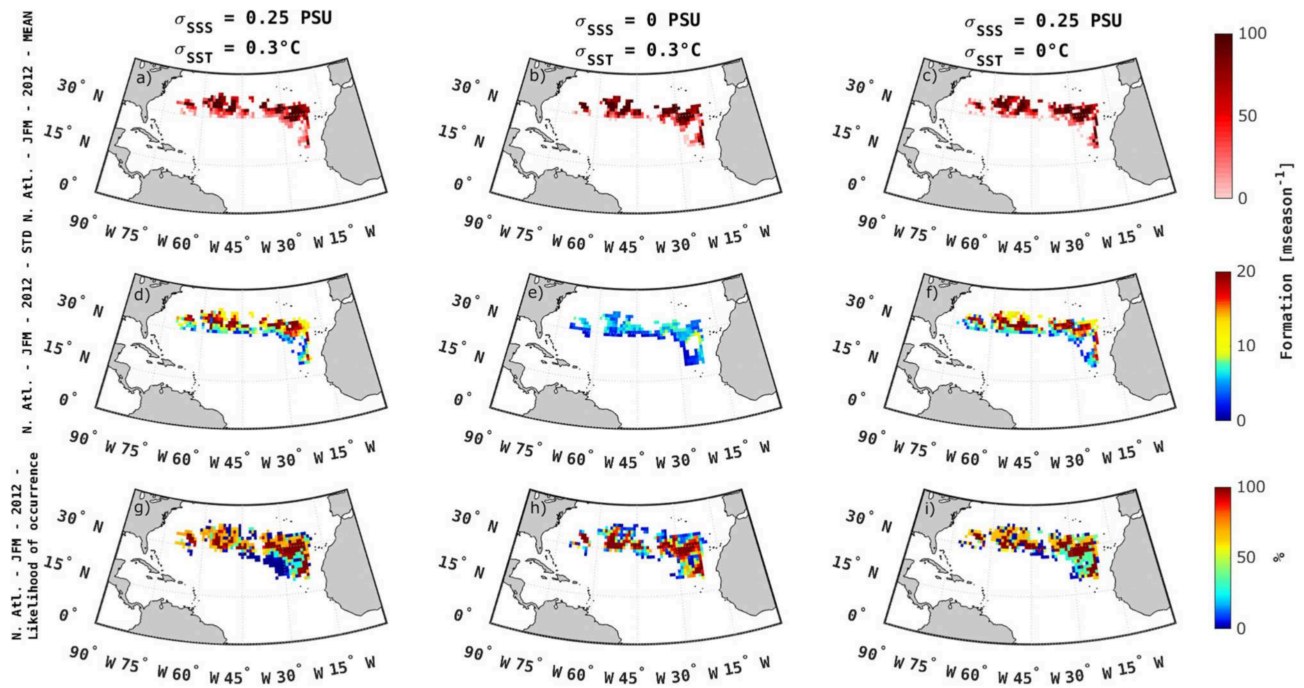

FIGURE 13 | Mean **(a–c)** and standard deviation **(d–f)** of formation in geographic space after 500 Monte-Carlo realisations during the winter months (JFM) in 2012 over the North Atlantic, as well as the uncertainty in the geographic distribution over the 500 Monte-Carlo realisations **(g–i)**. The Monte-Carlo simulation was run three times with uncertainties considered in both SMOS SSS and OSTIA SST (first column), only OSTIA SST (second column) and only SMOS SSS (last column).

estimate how the uncertainty in the satellite data propagates into the final formation estimates. By looking at formation in three coordinate systems (σ, θ–S, and geographic space), we are able to constrain the properties and location of water mass formation more accurately than with a single coordinate system.

A comparison with previous literature-based Mode Water properties shows that the satellite-derived formation of Mode Waters is shifted towards higher salinities and higher temperatures. In addition to errors in the underlying satellite data, this shift could be explained by recent climate change. The satellites may also capture processes that cannot be captured by the poor spatial coverage of *in-situ* measurements (Marsh and New, 1996; Banks et al., 2000; Alfultis and Cornillon, 2001; Gulev et al., 2003). In comparison to Argo ISAS data, the satellite-derived water mass properties are shifted towards lower salinities. Work done on L-band microwave radiometres has shown that the effect of freshwater lenses on the ocean surface after a rain event interferes with the signals retrieved by the instrument (Boutin et al., 2013; Santos-Garcia et al., 2014; Ma et al., 2015).

To understand to which extent satellite SSS and SST uncertainties contribute to the final estimates of formation, we apply a Monte-Carlo simulation. We are able to assess the uncertainty in the formation rate estimates and also the uncertainty in the geographic distribution of the water mass. With this, we proceed to alternately eliminate prescribed uncertainties in the underlying datasets in a sensitivity analysis. We find that most of the uncertainty is accounted for by uncertainties in SSS. This highlights the need for frequent and increasingly accurate satellite SSS data for the estimation of water mass formation.

Future work can be planned around several research avenues of increasing complexity. The various types of satellite data sources can be expanded by evaluating the impact of additional satellites/sensors—namely satellite SSS from Aquarius/SMAP missions. The same would apply for the data sources regarding heat and freshwater fluxes; for the latter, the corresponding uncertainties can also be introduced. Then, a more thorough analysis of the seasonal-to-inter-annual variability of density flux, transformation and formation can be performed—trying to link the inferred variability with oceanographic/climatic processes. More complex formulations taking into account, for instance, advection processes (and their relationship to ocean currents) would give a broader picture into the water mass formation spatio-temporal evolution. A computer vision algorithm to automatically and reliably detect peaks in water mass formation and map the corresponding geographic location is currently under finalisation. Future work could also explore the possibility of retrieving information on the evolution of satellite-measured surface water masses through the use of well-known parametres such as the Turner angle or Brunt-Väisälä frequency.

This study emphasises how synoptic satellite measurements of SSS and SST can be extremely valuable to infer water mass characteristics from space. Sustained future satellite SSS and SST measurements, possibly at increased spatial resolution and with higher accuracy, are therefore much needed remote sensing observations. Algorithm improvements along the lines described above would render the process of estimating water mass features from space easily operational. A systematic and increasingly accurate estimation of water mass distribution and variability would shed light onto physical and biogeochemical oceanographic processes (ocean circulation, ocean/atmosphere exchanges, nutrients and carbon cycles, etc.) of major relevance for climate and society at large.

AUTHOR CONTRIBUTIONS

AP: extended work initially done by MK under the supervision of RS and the code written by LC. RS: supervisor of AP and previous supervisor of MK. MK: trainee at ESRIN during 2010–11, started work on topic under supervision of RS. LC: software engineer wrote code formalising model initially found by MK in literature. DF: main supervisor of AP and manager of project.

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A Yellow Sea Monitoring Platform and Its Scientific Applications

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The Yellow Sea is one of the most productive continental shelves in the world. This large marine ecosystem is experiencing an epochal change in water temperature, stratification, nutrients, and subsequently in ecological diversity. Research-oriented monitoring of these changes requires a sustainable, multi-disciplinary approach. For this purpose, the Korea Institute of Ocean Science and Technology (KIOST) constructed the Socheongcho Ocean Research Station (S-ORS), a steel-framed tower-type platform, in the central Yellow Sea about 50 km off the western coast of the Korean Peninsula. This station is equipped with about forty sensors for interdisciplinary oceanographic observations. Since its construction in 2014, this station has continuously conducted scientific observations and provided qualified time series: physical oceanographic variables such as temperature, salinity, sea level pressure, wave, and current; biogeochemical variables such as chlorophyll-a, photosynthetically active radiation, and total suspended particles; atmospheric variables including air temperature, wind, greenhouse gasses, and air particles including black carbon. A prime advantage is that this platform has provided stable facilities including a wet lab where scientists can stay and experiment on *in situ* water samples. Several studies are in process to understand and characterize the evolution of environmental signals, including air-sea interaction, marine ecosystems, wave detection, and total suspended particles in the central Yellow Sea. This paper provides an overview of the research facilities, maintenance, observations, scientific achievements, and next steps of the S-ORS with highlighting this station as an open lab for interdisciplinary collaboration on multiscale process studies.

Keywords: Socheongcho Ocean Research Station (S-ORS), multi-disciplinary observation, long-term time series, steel-framed platform, continental shelf, OceanSITES

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INTRODUCTION

The Yellow Sea is a shallow, marginal sea in the northwest Pacific spanning about 1,000 km meridionally and 700 km zonally (see **Figure 1**). Albeit the small volume, this sea is one of the most productive marine ecosystems (Xie et al., 2002; Belkin, 2009). Scientists have reported that this sea is experiencing epochal, systematic changes in water properties associated with wind, precipitation, and currents bifurcated from the Kuroshio (Liao et al., 2015; Cai et al., 2017; Kim et al., 2018b). These environmental changes likely trigger a regime shift

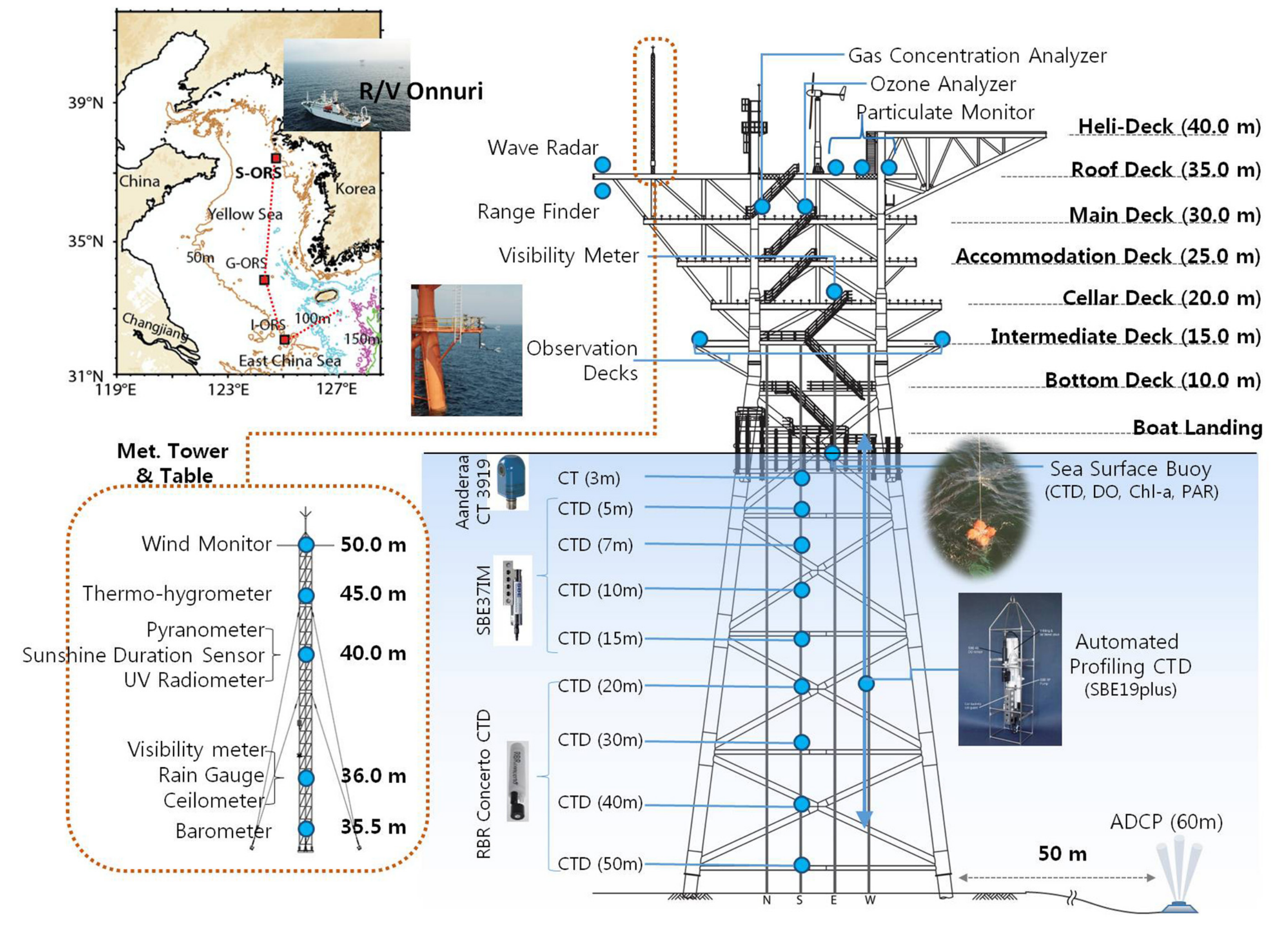

FIGURE 1 | Specification and major observation sensors of the Socheongcho Ocean Research Station (S-ORS), with its geographic location in the Yellow Sea (the upper left-hand map). The red dotted line on the map shows the cruise route of the research vessel during an annual field trip via three KORS, i.e., the S-ORS, the Gageocho Ocean Research Station (G-ORS), and the Ieodo Ocean Research Station (I-ORS) in summer.

in the ecological diversity of the Yellow Sea (Zhang et al., 2000). Such ecological implications raise the need for a sustainable, multi-disciplinary monitoring system. Surface buoy or bottom mooring type observations are not pertinent to this sea, primarily due to the harsh oceanic conditions and intensive fishing activities, nor does the Yellow Sea's shallowness allow typical Argo floats. We believe that a steel-framed structure is a unique alternative for a sustained, integral atmosphere-ocean observation system. A prototype of the steel-frame oceanographic tower is the Acqua Alta, constructed in 1970 to address hydraulic issues in the Adriatic Sea (Cavaleri, 2000). While this tower does not operate currently due to a revamping process, it had successfully produced air-sea observations for more than four decades without any deterioration on its steel frame.

The Korea Institute of Ocean Science and Technology (KIOST) has constructed three steel-framed tower-type Korea Ocean Research Stations (KORS) in the Yellow and East China Seas since 2003 (**Figure 1**; Ha et al., 2019). The first one is the Ieodo Ocean Research Station (I-ORS) in the northern East China Sea, a boundary between the Yellow Sea and the open ocean. The KIOST constructed the Gageocho (G-ORS) in 2009 and the Socheongcho Ocean Research Stations (S-ORS) in 2014 sequentially. Unfortunately, typhoon Muifa swept over the G-ORS in July 2011 and caused structural damage to this station. After its repair, this station has functioned in part concerning air-sea interaction by using the meteorological and optical sensors. After damage inspections on the G-ORS's structural frame, the S-ORS was designed to withstand various extreme conditions such as waves up to 18-m in height, 60 m/s winds, and 6.5 Richter-scale earthquakes. The planned lifetime of the S-ORS is 50 years while its fatigue lifetime being around 100 years.

A chief aim of these stations is to observe the meridional propagation of atmospheric and oceanic signals between the open ocean and the continental shelf. In this view, the I-ORS is pertinent to investigate oceanic signals from the open ocean into the continental shelf focusing on the hydraulic processes of a typhoon, current, internal wave, and riverine discharge (see Ha et al. (2019) for detailed information on ongoing researches utilizing the I-ORS). The S-ORS is, however, more suite to investigate continent-induced air-sea interactions in the Yellow Sea and also its intrinsic variability than the I-ORS. From an operational perspective, experimental tryouts with cutting-edge technology are examined on the S-ORS owing to the expandability of sensors, facilities with a wet lab and accommodation, as well as efficient logistics. After preliminary optimization, the measurement would be routinely operated on the I-ORS because of its restriction in resources and transportation. In this review, therefore, we highlight the S-ORS by specifying its detailed structure, demonstrating scientific applications, and sharing our next steps as an open lab for multiscale, interdisciplinary process studies.

THE SOCHEONGCHO OCEAN RESEARCH STATION (S-ORS)

Its Facilities, Instruments, and Measurements

The S-ORS sits on the eastern flank of the central trough of the Yellow Sea with a water depth of 50 m (37° 25′ 23.3″ N, 124° 44′ 16.9″ E). The S-ORS is composed of seven decks, as illustrated in **Figure 1**. A wind turbine and solar panels on the roof deck, and two diesel generators in the cellar deck supply the S-ORS with electricity. The core facilities – the main control room, switchgear room, and battery room – are located on the main deck for its general administration. Researchers are allowed on board this station on a routine basis roughly every month, by ship or helicopter via the boat landing and heli-deck. Up to forty people can stay at a time in the residence facilities on the main and accommodation decks, which consist of six spacious bedrooms, a public kitchen, a living room, and a rec center. There is a wet lab on the cellar deck, where scientists can carry out necessary processes to their water samples (**Figure 2**). The wet lab is equipped with FlowCAM and Hplc-flowcytometer to figure out the size and species composition of sampled phytoplankton. By taking advantage of this wet lab and on-site accommodation of the S-ORS, researchers can stay for several days for the immediate *in situ* analysis of water samples, which need strict procedures to avoid potential degradation during their storage and transportation. Also noteworthy are two observation decks on the northeast and southwest corners of the intermediate deck, which extend 6 m out over the sea. These extended decks aid data collection by minimizing any structural interference associated with the shade of the S-ORS and turbulent currents to the rear of this large-scale structure.

About forty instruments have worked on the S-ORS for multi-disciplinary researches and environmental monitoring (**Table 1**). A meteorological tower (wind, solar radiance, precipitation, air pressure, and temperature), air particle sensors ($PM_{2.5}$, PM_{10}, and black carbon), a gas concentration analyzer (CO, CO_2, H_2O, and CH_4), and an ozone analyzer are mounted on the roof deck. There is a radar-type two-dimensional wave monitoring instrument (Miros Wave and Current Radar; SM-050 MKIII) on the northeast rim of the roof deck. This wave sensor looks down onto the sea surface at an angle of 10°, generally identifying waves 100-m away from the station (Min et al., 2018). An electrical winch system on the intermediate deck operates four stainless steel cables, which allow instruments to be lowered into the water. The CTD sensors attached to one of the cables observe real-time temperature and salinity at fixed levels of 3, 7, 10, 15, 20, 30, 40, and 50 m during the water stratification period from May to November while the top CTD sensor works throughout the year. As a complementary measurement to the fixed-depth CTD observations, an automatic CTD profiling is in operation twice a day.

Also, we use a floating buoy to measure temperature, salinity, dissolved oxygen (DO), chlorophyll fluorescence, and photosynthetically active radiation (PAR) at the sea surface. An upward-looking 150 kHz acoustic Doppler current profiler (ADCP) is moored on the seafloor to observe vertical profiles of water currents and also for in-direct measurements of the vertical concentration of water particles. The ADCP is about 50-m away from the S-ORS to avoid artificial interference associated with the station's infrastructure.

Ship-Based Annual Survey

To assess the spatial representativeness of the oceanic time series obtained from the S-ORS we have annually carried out a research cruise on board the R/V Onnuri of KIOST by crossing Yellow Sea via the KORS during the summer (see the cruise route on the map in **Figure 1**). During this survey, we have routinely collected primary production, hyperspectral radiance, ocean color, and hydrographic profiles using both an underway CTD and a typical CTD. During the 2019 cruise, an ocean acidification monitoring buoy and a directional waverider buoy are situated in the vicinity of the S-ORS.

Maintenance

After the few years of test operations of the S-ORS by KIOST, the Korea Hydrographic and Oceanographic Agency (KHOA) has been responsible for managing the S-ORS with the agreement and cooperation of KIOST. As expected from shallow water observations, biofouling has been an issue for the underwater instruments, particularly the conductivity and oxygen sensors. We have tried several experiments to mitigate this biofouling issue with anti-fouling measures using copper tape, a UV-light bulb, or both, however, the most practical solution until now is to clean the sensors as frequently as possible. At around one-month intervals, KHOA conducts regular maintenance of the sensors by cleaning and recalibration based on *in situ* CTD profiling and water sampling.

Data Distribution

The satellite antenna on the roof deck of the S-ORS transmits real-time measurements via the Mugungwha V communication satellite to the data storage server at KHOA. These real-time and delayed-mode datasets are publically serviced via the Korea Ocean Observation and Forecasting System (KOOFS) website of KHOA[1]. OceanSITES, a global network for time series measurements from stationary observations, recently

[1] http://www.khoa.go.kr/koofs/eng/observation/obs_real.do

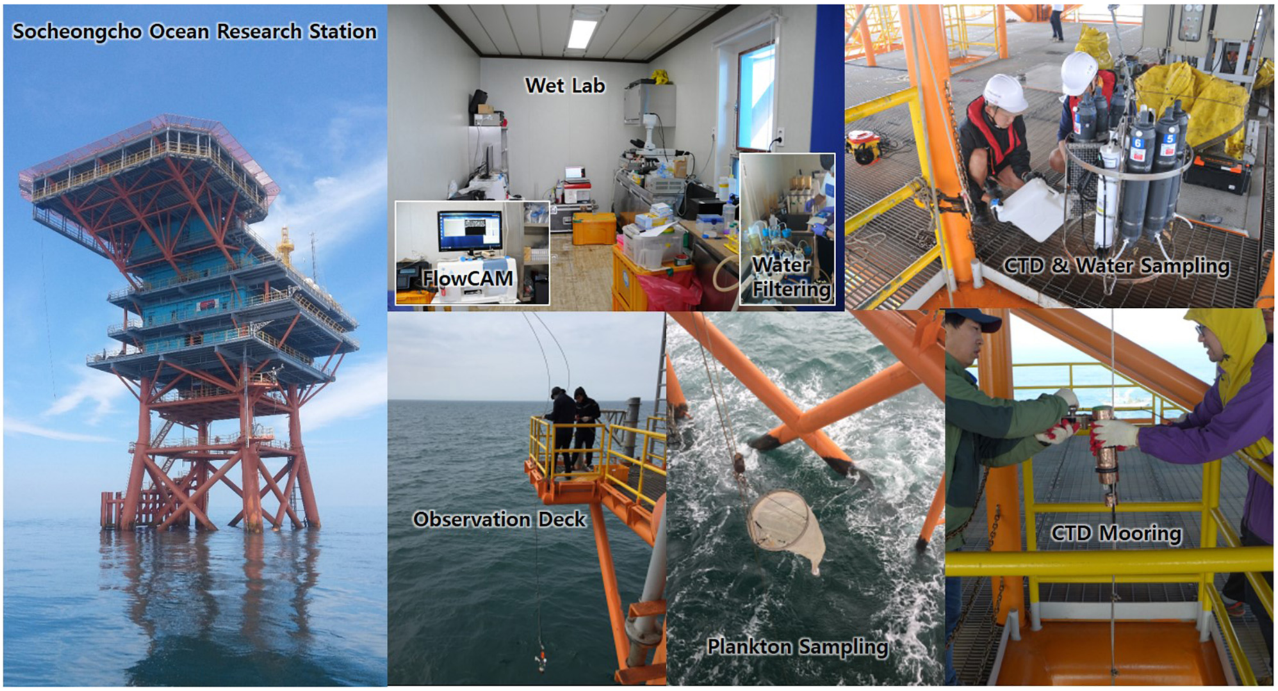

FIGURE 2 | An overview of the S-ORS: Research facilities and activities.

accepted the S-ORS and the other KORS, as pilot stations on the continental shelf. We have prepared to distribute the delayed mode time series via the global data center (GDAC) of OceanSITES by following its standard nomenclature and flag system.

SELECTIVE PROCESS STUDIES

Mixed Layer Depth and Air-Sea Interaction

An oceanic mixed layer modulates the exchange of heat, momentum, and biochemical compounds between the ocean and the atmosphere. Despite its implications for the marine ecosystem, air-sea interaction, and thus climate, the variability of the mixed layer is not well understood in the Yellow Sea, due to a scarcity of oceanic observations. Recently, the seasonal to daily variability of the mixed layer was investigated for April 21-October 15, 2015, using 10-minute interval CTD observations in tandem with atmospheric measurements from the atmospheric tower of the S-ORS (Kim et al., 2018a).

Three distinct periods comprising a fully-mixed stage until late April, a quasi-stable stage from late April to late July, and then a linearly falling stage at a rate of 2.6 m per month characterize the seasonal evolution of the mixed layer depth (MLD). This seasonal evolution was principally related to buoyancy forcing, particularly latent heat fluxes, which also had a gradually declining trend at a rate of -81.6 W/m^2 per month during the MLD's falling stage. On a shorter timescale, the MLD was significantly correlated with wind speed, except for the full-mixed stage. This MLD-wind relationship, however, was not stationary during our study period; a sharp drop of the correlations between the MLD and wind speed was estimated during middle July and middle August. During this period there were three heavy precipitation events – typhoons Chanhom, Halola, and Soudelor, passing near the S-ORS on July 12, July 28, and August 8, respectively. The rainfall on these three events was about a third of the total rainfall in 2015 near the S-ORS. The independent CTD casts during August 3-5 2015 revealed the existence of a 3 m-thick barrier layer over the mixed layer, indicating that heavy rainfall and its attendant freshwater runoffs from the surrounding rivers caused additional buoyancy forcing in the surface layer. This buoyancy seems to form a barrier layer in the lower part of the MLD. This barrier layer likely decoupled the mixed layer from atmospheric perturbation, resulting in reduced MLD variance to wind forcing (Kara et al., 2000; Kim et al., 2018a). These results highlight the role of atmospheric forcing on determining the MLD in the central Yellow Sea, as well as suggesting the possibility of a long-term monitoring study of air-sea interaction by the S-ORS.

Primary Production During the 2017 Spring Bloom

To understand phytoplankton bloom dynamics and thereby to access ecological implications in the Yellow Sea, scientists have conducted regular *in situ* measurements of chlorophyll fluorescence, PAR, hydrographic profiles, and irradiance at the S-ORS for more than six weeks from April to May. Also, we have obtained water samples at standard depths of 1, 10, 20, 30, 40 m, and at a depth of the subsurface chlorophyll maximum

TABLE 1 | List of the major observation sensors and variables of the S-ORS.

	Sensors Model (Manufacturer)	Variables
Oceanic Sensors	CT CT3919 (AANDERAA)	Temperature, Conductivity
	CTD RBR Concerto (RBR)	Temperature, Conductivity, Salinity, Depth
	CTD SBE37, SBE19plus (SeaBird)	Temperature, Conductivity, Salinity, Depth, DO, Chlorophyll-a, PAR
	SeapHOx SBE37SMP, SeaFET, SBE63 (SeaBird)	Temperature, Conductivity, Salinity, Depth, DO, pH
	ADCP WHSW300 (RDI)	Water Current
	Tidal Guage SM-140 (MIROS)	Sea Level Height, Wave Height, Wave Period
	Wave Monitoring SM-050 (MIROS)	Wave, Current
Meteorological Sensors	Wind Monitor 05106 (RM YOUNG)	Wind (10 min Avg.), Gust Wind
	Ultrasonic Wind Sensor VENTUS (Lufft)	Wind
	Thermo-hygrometer HMP155 (VAISALA)	Air Temperature, Humidity
	Barometer PTB210B (VAISALA)	Atmospheric Pressure
	Visibility Meter PWD-21 (VAISALA)	Visibility
	Pyranometer CMP21 (Kipp & Zonen)	Insolation
	Ultraviolet Radiometer MS-212D (Kipp & Zonen)	UV Insolation
	Sunshine Duration Meter MS-093 (EKO)	Sunshine Duration
	Rain Guage ERGH (ELP)	Rainfall
	3-D Sonic Anemometer CSAT3 (Campbell)	3-D Wind Turbulence
	Gas Analyzer EC-150 (Campbell)	CO_2, H_2O
Environmental Sensors	Continuous Ambient Particulate Monitor FH62C14 (Thermo)	$PM_{2.5}$, PM_{10}
	Multi-Angle Absorption Photometer 5012 (Thermo)	Black Carbon
	O_3 Monitoring 49i (Thermo Fisher)	Ozone
	Gas Concentration Analyzer G2401 (Picarro)	CO, CO_2, CH_4, H_2O
	Ceilometer CL31 (VAISALA)	Cloud

for the analysis of nutrients, chlorophyll-a, pigments, and the phytoplankton community structure, and primary production. In 2017, a spring bloom observation study was conducted for April 4-May 20. Concurrently, we collected total suspended particles (TSP) from the high volume aerosol sampler using Whatman 41 filter papers to understand the pollution levels associated with Asian dust (also known as yellow dust). The TSP samples were analyzed for 33 elements by ICP-MS after mixed acid decomposition.

The concentrations of chlorophyll-a, an indicator of phytoplankton biomass, varied 1.12∼7.38 μg/l, with its maximum on April 28. Consistently, the primary production ranged from 78 to 3,095 $mgCm^{-2}d^{-1}$ during the study period with a mean value of 974 $mgCm^{-2}d^{-1}$; its intrinsic variability coincided with the phytoplankton bloom. The biomass of phytoplankton and PAR were the main factors influencing the observed primary production. The observation that the population of *nanoflagellates* showed a significant correlation with the concentrations of chlorophyll-a indicates that the *nanoflagellates* were a dominant group in the observed spring blooms. Nitrate, phosphate, and silicate decreased continuously after April 5, while the N/P ratios showed a decreasing trend from the beginning of May. This discrepancy might indicate that the nitrate was one of the limiting factors for phytoplankton growth. Besides the general maximum phytoplankton bloom that occurred on April 28, two additional blooms existed during the study period. These *ad hoc* blooms seem to be related to the anthropogenic metals and surplus nutrients in the surface waters. The highest metal concentration for Al (5,041 ng/m^3) was observed at the *ad hoc* blooms. Also, the enrichment factor of twelve elements of Se, Cd, Sb, As, Pb, Mo, Zn, Sn, V, Ni, Cu, and Tl in the TSP samples was more than ten. These observations demonstrate that anthropogenic pollution-derived particles were dominant during those periods. These preliminary results seem to demonstrate that the primary productivity in the central Yellow Sea is, at least in part, influenced by surplus metal inputs associated with Asian dust originating from the continent.

Surface Wave

The S-ORS is an adequate research site for investigating wave-current interactions because of not only tidal currents as strong as 1 m/s but also the stability of this station, on which there are no significant fluctuations even in conditions with high waves and strong winds. A stereo wave imaging system on the S-ORS produced a high-quality time sequence of spatial wave images. Benetazzo et al. (2018) utilized these images to investigate the characteristic spatiotemporal length scales of linear and non-linear rogue waves, their power spectrum in a 3-D wavenumber and frequency domain, and the probability of the occurrence of a rogue wave. They argued that the rogue waves occurred ten times more frequently, i.e., one out of a hundred waves, than expected from a theoretical wave model in this study area. This stereo wave imaging system was moved to the G-ORS, where the tidal currents are much stronger than those near the S-ORS; hence, more frequent non-linear rogue waves are expected.

Validation of the Satellite Ocean Color and Operational Ocean Forecasting

An AERONET-OC spectrometer is installed on an extended steel frame on the southwest corner of the main deck, thus monitoring the radiance from the sea surface, including ocean color information without any structural interference. These data, currently serviced via the NASA website[2], have been used to validate the ocean color estimated by the GOCI satellite (Kim et al., 2015; Concha et al., 2019).

[2]https://aeronet.gsfc.nasa.gov/

The Korea Operational Oceanography System (KOOS) has worked to provide a 72-hour forecast of ocean states in terms of sea surface elevation, currents, winds, waves, hydrographic profiles in the seas around the Korean Peninsula. This system consists of various numerical models from atmospheric to oceanic models including Weather Research and Forecasting (WRF), KOOS-OPEM, Coastal KOOS, and a Simulating Waves Nearshore (SWAN) model. The KOOS takes advantage of the observed time series of water temperature, winds, and waves from the KORS for its skill assessment (Park et al., 2015). Intermittent experiments have been conducted near the S-ORS during the annual ship-based surveys by deploying various surface drifts equipped with GPS tracking systems. Choi et al. (2018) utilized drift information to validate the currents forecasted by the KOOS, hence trying to provide precise information to the Korea coast guard in the perspective of maritime search and rescue operation.

THE NEXT STEPS

The KIOST has plans to maximize the performance of the S-ORS, as well as to facilitate process studies as follows:

- Automatic and unmanned mobile vehicles including underwater gliders, AUVs, and airborne drones will be operated between the KORS to cover large areas of the Yellow Sea. The KORS can host these vehicles as docking and charging stations. The S-ORS will play a critical role as a testbed for these mobile observations.
- Real-time monitoring and near-future forecasting are needed for governments and relevant stakeholders for proactive approaches toward maritime accidents, red tides, hypoxia, typhoon, surge, marine pollution, etc. We plan to assimilate high-resolution spatiotemporal observations from both the KORS and mobile vehicles into the KOOS to improve the accuracy of prediction and service realistic oceanic fields, thus finally constructing a comprehensive ocean observation and prediction system in the Yellow Sea.
- As a shallow-water pilot station of OceanSITES, the S-ORS will be a local contributor to global collaborative studies. A research group that wants to take advantage of the S-ORS as well as its lab space is welcomed to contact the PI or coordinator of the KORS project to specify the experimental contents under a scientific theme to maximize its utilization.

CONCLUDING REMARKS

The S-ORS has provided high-quality, continuous time-series data for multi-disciplinary studies in the central Yellow Sea, including meteorological, physical, and biogeochemical data from more than forty sensors and research facilities. These data should be essential for researchers to understand better regional ecosystems, as well as for governments to have a proactive approach toward maritime issues. This station is designed to work for at least 50 years, thus able to provide data for comprehensive, interdisciplinary studies on climate change, as well as regional phenomena in the Yellow Sea. The S-ORS has sufficient research facilities that include a wet lab for staying scientists to experiment with real-time time series and *in situ* water samples. A research group can also bring their instruments or sensors to this platform for collaborating studies. As per rapidly developing intellectual and communication technologies in the oceanic observation field, the S-ORS aims to become a more automated ocean observation platform. Unmanned autonomous vehicle operations have been tested for several years to integrate temporal and spatial observations with the operational, ocean forecasting system. The S-ORS has hosted multiscale process studies as an open lab and as a local contributor to international collaborative studies.

AUTHOR CONTRIBUTIONS

J-YJ led the writing of this manuscript. YK and J-YJ wrote the manuscript based on the reports from JN, K-TK, and J-IK. J-YJ, YK, and YM generated figures and associated text. CJ contributed to the editing and organization of the manuscript. JN, K-TK, JJ, JL, I-KM, and JK conducted *in situ* observations on the S-ORS and processed the time series data. J-SS and D-SB edited the manuscript by providing corrections and clarifications. All authors reviewed the final version of this manuscript and approved it for publication.

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frontiers in Marine Science

REVIEW
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Multidisciplinary Observing in the World Ocean's Oxygen Minimum Zone Regions: From Climate to Fish — The VOICE Initiative

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Multidisciplinary ocean observing activities provide critical ocean information to satisfy ever-changing socioeconomic needs and require coordinated implementation. The upper oxycline (transition between high and low oxygen waters) is fundamentally important for the ecosystem structure and can be a useful proxy for multiple observing objectives connected to eastern boundary systems (EBSs) that neighbor oxygen minimum zones (OMZs). The variability of the oxycline and its impact on the ecosystem (VOICE) initiative demonstrates how societal benefits drive the need for integration and optimization of biological, biogeochemical, and physical components of regional ocean observing related to EBS. In liaison with the Global Ocean Oxygen Network, VOICE creates a roadmap toward observation-model syntheses for a comprehensive understanding of selected oxycline-dependent objectives. Local to global effects, such as habitat compression or deoxygenation trends, prompt for comprehensive observing of the oxycline on various space and time scales, and for an increased awareness of its impact on ecosystem services. Building on the Framework for Ocean Observing (FOO), we present a first readiness level assessment for ocean observing of the oxycline in EBS. This was to determine current ocean observing design and future needs in EBS regions (e.g., the California Current System, the Equatorial Eastern Pacific off Ecuador, the Peru–Chile Current system, the Northern Benguela off Namibia, etc.) building on the FOO strategy. We choose regional champions to assess the ocean observing design elements proposed in the FOO, namely, requirement processes, coordination of observational elements, and data management and information products and the related best practices. The readiness level for the FOO elements was derived for each EBS through a similar and very general *ad hoc* questionnaire. Despite some weaknesses in the questionnaire design and its completion, an assessment was achievable. We found that fisheries and ecosystem management are a societal requirement for all regions, but maturity levels of observational elements and data management and information products differ substantially. Identification of relevant stakeholders, developing strategies for readiness level improvements, and building and sustaining infrastructure capacity to implement these strategies are fundamental milestones for the VOICE initiative over the next 2–5 years and beyond.

Keywords: oxygen minimum zones, oxycline, ocean observing system, multidisciplinary, readiness level, ecosystem

INTRODUCTION

Challenges for Multidisciplinary Sustained Ocean Observations

The physical, biogeochemical, and ecosystem state of the ocean is shaped by multiple processes that operate in parallel and interact with each other. The interactions might be negligible, linear, or highly non-linear and often cross disciplines, time scales (subseconds to centuries and longer), and boundaries (atmosphere, cryosphere, land). Comprehensive observing requires a mix of *in situ* and remote sensing observing technology hosted physically by observation platforms. Thus, the motivating ocean observing objective must be known (societal benefit of an ocean product), and data integration and ocean observing product generation, including dissemination, are important elements.

The Framework for Ocean Observing (FOO: UNESCO, 2012; **Figure 1**) provides guidance for structuring ocean observing, from societal requirements, monitoring the ocean via observations, data integration, and downstream services related to ocean observing products, including ocean observing codesign aspects for product improvement and new product creation. The FOO is a strategic document that provides valuable guidelines for assessing ocean observing problems, but it is not an implementation plan for specific ocean observing applications.

The "loop" that is executed when applying the FOO principles to a certain observing objective (e.g., seasonal cycle of habitat compression in a certain area) is also called the "ocean observing value chain." Value chain is a concept adopted from economics that describes a process in which a system is organized through subsystems, each adding value with inputs, transformation processes, and outputs. By evaluating the value chain for a region or an observing objective, it reveals not only the contributing structural elements and their linkages but sets the options for optimization of the system (following Porter, 1985). The total value delivered by the system is the sum of the value of all subsystems. The value chain activities are separated into primary activities (operations, distribution, trade) and secondary activities (research and development, human resources).

To determine the ocean observing status for a certain objective, the activities within the FOO ocean observing value chain are analyzed. The *primary activities* are (i) requirement processes, (ii) coordination of observational elements, and (iii) data management and information products. These three activities are referred to here as "the FOO pillars." The *secondary activities* are identical to those described in economics: research and development, and human resources. To evaluate the maturity of the primary and secondary activities, a readiness level scheme, such as proposed by the FOO, can be applied for each of the FOO pillars. In **Table 1**, we summarize measures and metrics characteristic of three basic readiness levels (concept, mature, and pilot) describing the status of the individual ocean observing activities within each region considered in this study. The FOO (UNESCO, 2012) uses a more refined nine-level readiness level

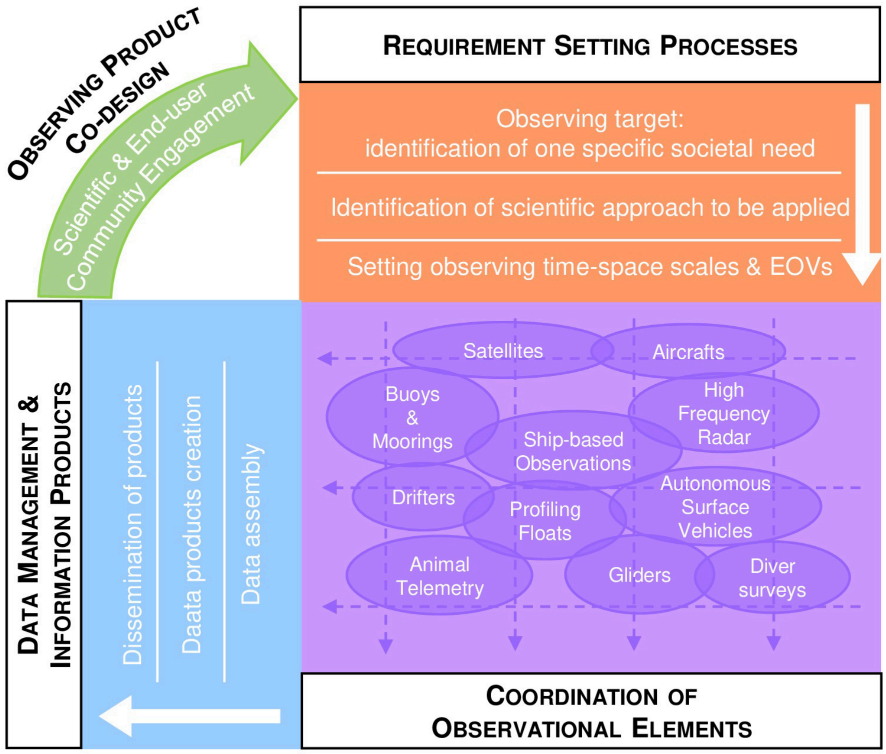

FIGURE 1 | Conceptual structure for an ocean observing value chain designed to match the original structure of the Framework for Ocean Observing (FOO) (Adapted from the FOO, 2012).

scale nested within the basic three level scales: from concept (levels 1–3) and pilot (levels 4–6) to mature (levels 7–9). In this paper, we assign either one specific level or a range of levels (e.g., 4–5) by comparing, for example, to what extent the requirement processes set in a given region match those described by the FOO readiness level scale.

One objective in defining an observing system (including the whole value chain) is to achieve maximum efficiency (optimization) within the constraint of enabling sustainability and meeting sponsoring organizations' requirements. For example, the observations executed in the context of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS) are activities that are cosponsored by the Intergovernmental Oceanographic Commission of UNESCO, the World Meteorological Organization, the International Council for Science, and the UN Environment. The sponsoring organizations expect multiple uses of the data. This means, for example, that certain elements of the ocean observing value chain for monitoring the seasonal variability of habitat compression for fisheries advice, which may deliver to operational aspects in the GOOS, may also be used in the ocean observing value chain for long-term trends in deoxygenation, as a clear GCOS topic. The two observing objectives obviously differ in their respective time scales and requirements on data quality, and also the data integrators and users of the products are different, but the observing infrastructure may overlap with each other and also with other GOOS and GCOS observing value chains. As such, the "integration for optimization" of several ocean observing objectives is a complex process that probably is best initiated by assessing and analyzing the functionality and elements of the regional ocean observing value chains.

In this paper, we present the variability of the oxycline and its impact on the ecosystem (VOICE) as initiative which attempts to (i) identify ocean observing value chains that are in operation in several eastern boundary systems (EBSs) around the globe and (ii) to assess their apparent readiness levels with respect to all three pillars of the FOO, with a particular observing objective in mind.

Introduction to the OMZ and Eastern Boundary System Regions

Oxygen minimum zones (OMZs) in the global ocean are oceanic regions with low oxygen concentrations as a result of high ratios of the rate of oxygen consumption to ocean ventilation in the mesopelagic ocean (Wyrtki, 1962; Luyten et al., 1983; Karstensen et al., 2008; Paulmier and Ruiz-Pino, 2009). OMZs are found neighboring EBS in the Atlantic and Pacific oceans and also in the northern Indian Ocean (see **Figure 2** for the VOICE regions). OMZs are high in nutrient content and exchanges between OMZ and EBS create highly productive biological regions with high biomass and primary and secondary productivity, which in turn support important fisheries. In addition to natural variability, the EBSs are under the impact of human activities due to their

TABLE 1 | Readiness levels for ocean observing value chain assessments adopted for the VOICE initiative.

Readiness levels	Requirements processes	Coordination of observational elements	Data management and information products
Mature			
	Ongoing international community support End user needs satisfied, stable and long-term "mission," even sustained mission (EOV stage)	Quality specifications met, peer reviewed documentation, sustained indefinitely with periodic review	Distribution and management of data, free access, utility assessment Data products routinely available, user groups consultation
Pilot			
	Measurement strategy verified at sea (time, space) Requirement for operational environment and platform and sensor constraints	Pilot project in operational environment International governance and commitments Maintenance schedule and servicing logistics	Quality control and assurance, calibration Data policy Demonstration of system wide use and availability
Concept			
	Idea level, documentation, and proof of concept via feasibility study	What will be used Feasibility testing and documentation Strategy for operations	Specify a data model, interoperability strategy, and expert review

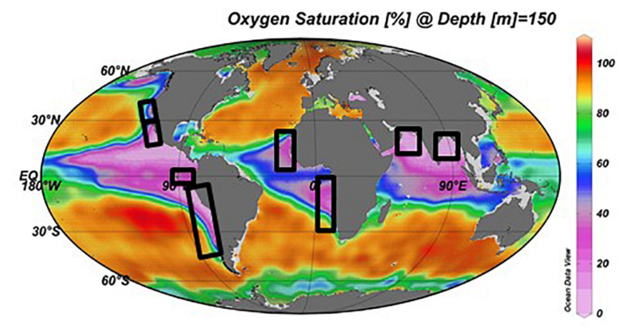

FIGURE 2 | Location of selected VOICE regions overlain on top of the global map of annual oxygen saturation (%) at 150 m depth. Regions included in VOICE: the oxygen minimum zone/eastern boundary systems (EBSs) (OMZ/EBS), the California Current System (US West coast and the Southern California Current system off Mexico), the Equatorial Eastern Pacific off Ecuador, the Peru–Chile Current system, West Africa off Senegal and Cape Verde Islands, the northern Benguela off Namibia, and the Northern Indian Ocean (Bay of Bengal and Arabian Sea).

proximity to coasts. The upwelling EBSs cover ∼0.01% of the global ocean area but sustain ∼20% of the world's wild fisheries (Pauly and Christensen, 1995).

The ecosystem functioning of upwelling EBS is an interlinked multidisciplinary problem. Cross-shelf processes drive the exchange of water between the continental shelf OMZ and boundary currents, leading to the import and export of, for example, heat, freshwater, sediments, nutrients, plankton, and fish larvae. Coastal upwelling, which is associated with vertical and horizontal water transport, is a physical process of particular importance. Coastal upwelling regulates primary productivity and drives the major fisheries in the upwelling EBS due to persistent winds (e.g., Bakun and Nelson, 1991; Albert et al., 2010; Desbiolles et al., 2016; Kämpf and Chapman, 2016) and bottom friction. Upwelling systems respond to local forcing but likewise are impacted by open ocean conditions (Gibbs et al., 1998; Palóczy et al., 2014).

Upwelling systems are particularly vulnerable to stressors. Regional-scale drivers and pressures may include commercial and recreational overfishing, sea-ranching aquaculture, oil and gas development and seabed mining, shipping, dredging, and waste disposal, and regional manifestations of climate change (see Hayes et al., 2012 for an example assessment for a well-managed global system operated in the context of the Integrated Marine Observing System/Blue Link of Australia). Given the multiple socioeconomic societally relevant activities in the EBS regions, there is considerable interest in observing and monitoring these areas.

The greatest concentration of commercial and recreational wild fishing effort is on the continental shelves and margins and includes both demersal and pelagic resources. For example, the highly productive surface waters off West Africa and in the Peru–Chile Current system, where OMZs are very close to the EBS fishing areas, support valuable commercial and recreational fisheries (Prince and Goodyear, 2006; Chavez et al., 2008; Stramma et al., 2011; Gutiérrez et al., 2016). Groundfish fisheries are economically important in some EBS, and fisheries species show species-specific responses to near-bottom oxygen levels (Keller et al., 2017). Aquaculture is also expanding rapidly to feed a growing global human population. Sea-ranching aquaculture relies on raising fish in fixed locations and often deals with high densities of animals, which may impact local biogeochemical oceanic and coastal conditions (i.e., pH and oxygen). Aquaculture operations may also be vulnerable to changing ocean conditions. For example, oyster hatcheries in Oregon, United States, experienced significant economic losses when oyster seed production collapsed due to the upwelling of more acidic waters (Barton et al., 2012).

Sea level rise, changes in ocean circulation and stratification, increases in tropical cyclone intensity, ocean acidification, and oxygen loss are manifestations of ongoing climate change. For instance, off the US West Coast, Feely et al. (2008) showed evidence of upwelling of "acidified" water onto the shelf. Low pH conditions affect shell dissolution in pteropods, which is an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem (Bednaršek et al., 2014). Sustained ocean observing systems provide an excellent opportunity to monitor these physicochemical changes and their ecosystem impacts.

Offshore oil or gas reserves and production areas are present off West Africa and transportation related to these commercial ventures is increasing in this upwelling EBS region. Similarly, ballast water exchanges along shipping lanes along the Atlantic and Pacific shorelines can introduce alien species that could subsequently harm ecosystems. Marine debris, particularly plastics, can have deleterious effects on all marine animals in the food chain. For turtles, seabirds, and whales, smothering, ingestion, and entanglement are threats and can also serve as a vector for biological invasions (Gregory, 2009). In EBS regions, alongshore currents might exacerbate the problem.

Since the OMZs play a role in the dynamics of the EBS, improving our understanding of EBS and fish, and thereby improving fisheries management and enhancing food security, are key long-term goals of VOICE. Fisheries harvests are an ecosystem service and only become a stressor when overfishing occurs.

Ocean Observing in the VOICE Regions

The GOOS in EBS Regions

Because VOICE is motivated by the application of the FOO and as such is linked to GOOS, we first consider how ocean observing efforts in the EBS regions are visible on the global from the perspective of GOOS. To track long-term observing efforts, GOOS relies on the information collected and made available by the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) *in situ* Observing Programs Support Centre (JCOMMOPS), which assembles information about when, where, and which observations have been executed and by whom. JCOMMOPS does not manage the actual observational data coming from various observational platforms but, rather, assembles all their metadata information (including the link to data centers that host the observational data).

By making use of the metadata in JCOMMOPS, we present here a first assessment of EBS ocean observations. JCOMMOPS operates at the boundary between "coordination of observational elements" and "data management and information products" (the second and third FOO pillars). This means that if missing information needed for analyses has not been incorporated into an integrated data aggregate or it is not adequately described in the metadata, then JCOMMOPS can coordinate the needed updates. Likewise, it could also be that the metadata are not complete or made available via the agreed data assembly centers.

Note that our assessment only considers the GOOS observing networks: profiling drifters Argo, Ship-Based Hydrographic Investigation Program, Global Sea Level Observing System, global network of open ocean time series stations (OceanSITES), Ships Observations Team, and Data Buoy Cooperation Panel. We use an example from the upwelling EBS region off West Africa in the Southeast Atlantic considering the VOICE relevant exclusive economic zones (EEZs) of the following countries: Republic of Congo, Republic of Angola (VOICE representative), Namibia (VOICE representative), and the relevant part of the South African EEZ (VOICE representative). JCOMMOPS lists for this region 46 observing platforms when we consider all possible levels of observing status (probable, confirmed, registered, operational, closed, inactive). From the JCOMMOPS metadata, it is evident that the platforms include 25 Argo floats, 11 Ships Observations Team ships, one Global Sea Level Observing System sea level station, and nine Data Buoy Cooperation Panel surface drifters. The parameters observed (numbers in brackets denote the number of platforms in the JCOMMOPS metadata base) are subsurface pressure, temperature, salinity (25), bulk sea-surface temperature (8), air temperature (7), air pressure (7), relative humidity (7), and oxygen (1). Observations are executed by the following countries: United States (16), Germany (12), United Kingdom (7), France (4), European Union (3), and four platforms do not specify the responsible country.

At this stage, we have to acknowledge that very few of the observing efforts are apparently reflected in the JCOMMOPS metadata base, meaning very few are "visible" in the GOOS and GCOS observing coordination. In contrast, a search for research cruises in the Pan-European infrastructure for ocean and marine data management (SeaDataNet[1]) reveals 321 research cruises for the Southeast Atlantic (covering the period 1975–2016). It is clear that better linkage of international metadata bases is required to make observing efforts visible and in turn accessible for global analyses of current capacities and gaps in ocean observing.

Ocean Observing in EBS Regions From a Fisheries View

Fisheries are a major societal driver for ocean observing in the EBS regions. The need for information on target species, their food webs, and habitats can be informed from dedicated observing by national agencies in the respective EBS countries. One very successful and long-standing observing effort that combines fish stock assessments and capacity development is organized via the *Centre for Development Cooperation in Fisheries* through operations aboard the Norwegian research vessel (RV) "Dr. Fridtjof Nansen" in EBS waters off Angola. The "RV Nansen" campaigns include the observation of biological/ecosystem variables, biogeochemistry, and physical oceanography. Moreover, meteorological variables are observed.

Because access to the "RV Nansen" data is subject to specific restrictions, data integration, beyond fish stock assessments, is not always fully explored. Likewise, the existence of the data and the observing efforts are not visible through JCOMMOPS and hence are not recognized as a contribution to the GOOS. Tchipalanga et al. (2018) provide an example of a typical "bottle neck" case in the FOO context: they found that further time series research on physical data from RV Nansen cruises revealed new insight into fish stock dynamics, creating the potential for prediction and thus better management. In the FOO ocean observing value chain framework, the Tchipalanga et al. (2018) example demonstrates that by bringing the third FOO Pillar "Data Management and Information Products" from Pilot readiness levels 5 (verification) to readiness level 6 (demonstration of availability, use, interoperability), a different class of ocean observing product is made available in the Angolan EBS. This development of a *primary activity* in the FOO (the

[1] https://www.seadatanet.org/Metadata

three "pillars") was only possible because of parallel support of *secondary activities* (research and development, and human resources; see Tchipalanga et al., 2018).

Satellite Observing

Another data source crucial for monitoring the EBS is satellite remote sensing data with multiannual coverage. Ocean color is a valuable proxy for many biogeochemical relevant parameters (e.g., chlorophyll concentration), as well as dynamics such as the absolute dynamic topography or the sea level anomaly. Horizontal resolution is often a limitation, and the land/sea transition can generate data problems and large uncertainties.

In upwelling EBS regions, wind forcing is of considerable interest (Bakun and Nelson, 1991). The wind exhibits a drop-off in a narrow strip close to the coast which the scatterometer data cannot document due to the 25-km blind strip close to the coast. On the other hand, altimeters on board ENVISAT, Jason-1, Jason-2, and SARAL satellites are able to document the spatial variability of the mean wind drop-off near the coast (Astudillo et al., 2017). This offers promising routes for the study of upwelling EBS with the upcoming Surface Water Ocean Topography altimeter[2].

THE VOICE INITIATIVE

The IMSOO[3] Workshop

The concept behind the VOICE initiative was developed during a workshop on Integrating Multidisciplinary Sustained Ocean Observations (IMSOO) held in February 2017 (Palacz et al., 2017a) and was designed to address one of the three IMSOO themes on *Integrated and Multidisciplinary Ocean Observing of Oxygen Minimum Zones* (the other two were on plankton observations and on boundary currents). The IMSOO-OMZ group decided to define an initiative that will address a first application of the FOO strategy (see the section "Introduction") and to undertake an assessment of the observing requirements, the existing and planned observing infrastructure, and the data integration and dissemination system in OMZ regions. The next step, based on the assessment in step 1, will be the development of possible implementation plans for improving the readiness levels of the FOO pillars in the OMZ regions. It was decided that the implementation plan must include a strategy for "data sharing standards" for multidisciplinary, multiplatform observations developing scientific strategies and also for creating suitable products to respond to the societal requirements identified for observing systems.

As an outcome, an overarching question, linked to multiple societal drivers for OMZ observing (e.g., fisheries, aquaculture, OMZ expansion, biodiversity changes, greenhouse gas emissions, carbon sequestration), was agreed upon for the proposed IMSOO-OMZ activity: *"How do changing OMZs affect the spatiotemporal distribution, productivity, and trophic structure of benthic and pelagic communities?"*

[2]https://swot.jpl.nasa.gov/mission.htm

[3]Implementation of Multidisciplinary Sustained Ocean Observations

However, realizing that many ocean observing value chains are associated with the above question, more specific but related scientific questions helped to narrow down the assessment space:

- *What are the physical mechanisms controlling/influencing oxygen supply to OMZs?*
- *What are the biological components controlling/influencing oxygen consumption?*
- *How does bentho-pelagic coupling affect biogeochemical and ecological feedbacks?*
- *What is the role of microbial community metabolism on the development of OMZs?*
- *What is the bottom-up effect of changing OMZs on the trophic structure?*
- *How does the fish biomass and community structure change in relation to a changing OMZ?*

From this overarching set of questions, the IMSOO-OMZ working group discussed approaches to propose fit-for-purpose, multidisciplinary ocean observing systems for OMZ regions. To do so, questions related to sustainability also need to be addressed. Therefore, societal impacts and benefits of the planned project were discussed considering the three broad GOOS application areas: (i) climate, (ii) operational services, and (iii) marine ecosystem health. These areas contribute to a large number of the United Nations Sustainable Development Goals (UN-SDGs), and in particular to SDG 13 and 14 addressing "Climate action" and "Life below water," respectively.

Multiple ocean observing value chains need to be assessed and analyzed. This assessment is the first step toward optimization—with "optimization by integration" meaning, for example, determining the potential for multiple uses of data, observing, integration, and dissemination infrastructure. An example of an optimization by integration is to use an observing platform for short-term oxycline variability (e.g., autonomous underwater electric gliders) as well as estimating decadal oxygen trends. In principle, this is an easy task; however, the climate application (decadal oxygen trend) requires a much higher precision and, as such, a different calibration effort for the glider oxygen sensor. To make the oxycline glider mission "fit-for-the climate purpose," it is most important to convey the additional request to the glider operator. Moreover, the glider operator needs guidelines (Best Practices; Pearlman et al., 2019) and also funding to perform the necessary calibration.

Based on *a priori* knowledge on the current observing systems (see also the section "The GOOS in EBS Regions"), certain challenges for the fit-for-purpose OMZ observing systems were identified at the IMSOO meeting, such as (i) better constrained biogeochemical fluxes (in particular respiration), (ii) temporal and spatially better resolved physical supply pathways of oxygen, (iii) improved model constraints on atmospheric/wind forcing, and (iv) increased understanding of the impacts of OMZs on changes in biological community structure and productivity.

Technology requirements were briefly considered concluding that a complementary approach of ship-based, fixed-point, autonomous, and satellite remote-sensing observations are needed to survey the relevant time and space scales for describing the phenomena associated with OMZ-relevant processes. The issue of scale, regional versus global, was raised in the context of phenomena and observations and modeling feasibility. The IMSOO-OMZ group concluded that, currently, the focus of demonstration activities for the fit-for-purpose observing system should be confined to the regional scale, taking into account not only the financial feasibility but also the increasing complexity when basin scale processes are included by integrating a wider range of contributing processes. Building on existing and forthcoming initiatives, a multidisciplinary OMZ project would be implementable in a number of key geographic regions, such as the California Current System (US West coast and the Southern California Current system off Mexico), the Equatorial Eastern Pacific off Ecuador, the Peru–Chile Current system, West Africa off Senegal and Cape Verde Islands, the northern Benguela off Namibia, and the Northern Indian Ocean (Bay of Bengal and Arabian Sea) (**Figure 2**). The choice of these nine OMZ regions was partly based on published maps of the highest economic vulnerability depending on the success of fisheries in a given country (Allison et al., 2009).

Possible challenges relating to implementation of the recommended OMZ project include: (i) securing financial resources for a sustainable observation program, (ii) legality of working in EEZs, (iii) accessing historical and current data, and (iv) technological limitations in instrument and sensor development.

Setting the Scientific Question for VOICE

To address the needs identified by the IMSOO-OMZ workshop, it was decided to define a "demonstration project," which would focus on a specific key feature of the OMZ that is of high relevance in the context of many of the scientific objectives, namely, the depth of the upper oxycline (**Figure 3**). The upper oxycline depth is constrained by a delicate balance between physical, biogeochemical, and biological processes, which interact non-linearly, particularly through mesoscale to submesoscale dynamics and is an ideal environment to test impacts of observations and models on dynamics hypotheses. We show here for orientation the oxycline defined by the difference in oxygen concentrations in the surface waters (between 70 and 10 m) (**Figure 3**).

Because of the fundamental impact of oxygen on almost all marine life (Breitburg et al., 2018), as well as biogeochemical cycling processes, the oxycline sharpness, and its location impact both biotic and abiotic processes, and its changes have significant potential impacts on entire ecosystems. Both models and observations reveal that oxycline variability is driven by a balance of biological, biogeochemical, and physical processes. Therefore, an IMSOO demonstration project focusing on the oxycline features of all OMZ systems of interest, with colocated, multidisciplinary sustained ocean observations, will have benefit for society.

It was acknowledged that oxycline dynamics do not encompass all processes controlling OMZ formation and change. Nonetheless, the focused topic of the VOICE has a tractable scope, for which tangible implementation plans could be further developed. To identify a user group, the OMZ focus was further narrowed down to the regional observing of oxycline-related processes in the OMZ-neighboring EBS regions.

FOO Readiness Level Assessments in VOICE Regions

Assessing ocean observing systems with respect to the oxycline topic involves a comprehensive analysis of the current capacities set against the phenomena and essential ocean variables (EOV[4]) associated with oxycline time and space variability, the spatiotemporal sampling design requirements, as well as platform, instrument, and sensor requirements.

During the IMSOO workshop, a preliminary list of such requirements was produced (Palacz et al., 2017a) and assembled into an *ad hoc* questionnaire to be sent to key stakeholders in targeted EBS regions (**Appendix** in **Supplementary Material**). Initially targeting a global representation, we realized in the scoping process that we managed to also interest ocean stakeholders (scientists, fisheries agencies) in the Southern California Current system off Mexico and the Equatorial Eastern Tropical Pacific off Ecuador in the VOICE initiative, while for other regions (e.g., Oman, Iran), these attempts were not successful.

To gather information for this assessment, we decided to reach out to key stakeholders to get their inputs. Given this was the first FOO implementation approach to describe readiness levels for multidisciplinary observing, and recognizing the limited expertise in the VOICE group in designing stakeholder questionnaires, deficiencies in the questionnaire precluded rigorous statistical analysis.

The design of the questionnaire addressed a need for simple, clearly articulated objectives that highlight our topic of interest, namely, the readiness level assessment of all the necessary elements for ocean observing of the oxycline, building on the FOO elements, and the type of respondents. Ocean observing related to OMZs/EBS and connected to the oxycline has global dimensions and thus immediately poses the problem of selecting a target audience for the questionnaire. For practical reasons, but acknowledging that the results will not be representative from a statistical point of view, we sent our questionnaire to a small sample (a dozen) of potential respondents that extended the initial IMSOO-OMZ group. Based on recommendations, one or two regional champions per EBS were selected that acted as representatives but without a formal application process. The questionnaires were completed by individuals or groups of two or three persons who had reasonable knowledge of the ocean observing efforts in the studied EBS regions. FOO design elements were assessed for requirement processes, coordination of observational elements, and data management and information products.

All aspects of questionnaire design and its results are seen as contributions to the anticipated end product of the VOICE initiative, which is a blueprint of multidisciplinary sustained ocean observing in EBS regions. The blueprint should outline a strategy on the minimum and optimal set of observational and modeling requirements for a fit-for-purpose system that is

[4] www.goosocean.org/eov

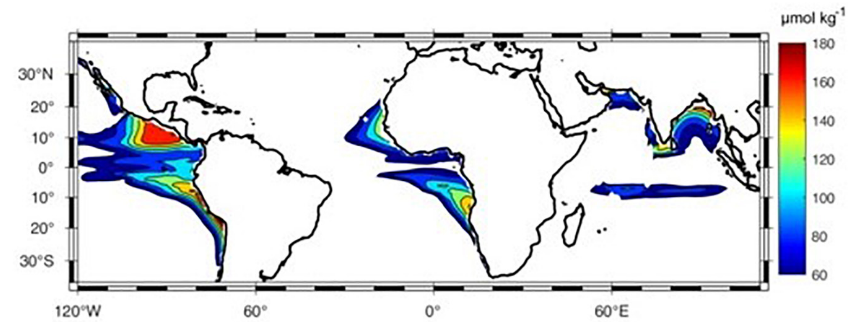

FIGURE 3 | Distribution of the oxygen difference between 70 and 10 m depth (concentrations < 60 μmol kg^{-1} have been omitted) based on an oxygen climatology. Data from Schmidtko et al. (2017).

capable of informing society about observing outcomes related to the variability of the oxycline (e.g., habitat compression, deoxygenation) and as an integrative part of the GOOS (Palacz et al., 2017b). The blueprint would be available to implement in any region, but unless the regional requirements are compatible with VOICE, they would not be taken into consideration when drafting the blueprint. Planning of VOICE was split in two different stages: the preparatory stage (2017–2019) and the implementation stage (2019–2022) (**Figure 4**). For a region to become a potential beneficiary of VOICE implementation activities, interest among its stakeholders in one or more of the VOICE questions needs to be demonstrated.

The questions were posed in the context of the overarching issue of "How do changing OMZs affect the spatiotemporal distribution, productivity, and trophic structure of the benthic and pelagic communities?" as stated in the IMSOO workshop report (Palacz et al., 2017a). However, bearing in mind the objectives of VOICE, the participants were asked to specifically focus, if possible, on the aspect of oxycline variability and its impacts on the ecosystem in "their" EBS. In our case, the questionnaire should be considered an initial semiquantitative effort in what should be a multistep process of assessing progress against the requirements for ocean observations. We acknowledge that there is uncertainty about false negatives in the results shown in the following tables and figures, meaning that some empty cells might simply represent a lack of knowledge and not a lack of observing efforts. Our analysis was consequently geared toward what we know (full cells) rather than what we know less about (empty cells). We also strongly emphasize that the ultimate goal of the readiness level assessment was not to discard the low readiness level components of the observing system (i.e., some regions) but rather to promote efforts leading to a gradual increase in the readiness level where it is most needed. The readiness level assessment from concept to pilot or mature (FOO, UNESCO, 2012; **Table 1**) includes maturity and integrity of requirements set for observations, current observing capability, and data and information product management for both the capability and the fitness for purpose.

Readiness level assessment and timeline to achieve maturity depends on the specific observing objective and can be region specific. There are clear interlinkages between the three FOO pillars notably in assigning readiness level, and one cannot be judged independently of the others. VOICE will realize the principles of FOO, going through the complete cycle from requirement setting to increasing readiness level of observations to optimized data management and information product delivery (**Figure 1**).

Requirement Setting Processes: The First FOO Pillar

The first FOO pillar (FOO1) seeks to assess the societal needs in terms of the environment or ecosystem information required to address specific observing objectives. This pillar also includes the observing approach to be used to respond to the observing objectives of relevance to VOICE. In other words, it asks, "What observing product is required?" and "How do we need to observe and integrate the data to create the product?" To assess the readiness level of the FOO1, a list of questions was formulated in the questionnaires (**Table 2**). The analysis was made by building a master answer file with all EBS regions and designing a graphical representation of the synthesized information (**Figures 5**, **6**).

We included in the questionnaire design all EOVs,[5] related to physics, climate, biogeochemistry, biology, and ecosystems. Although several BioEco EOVs might be considered less mature or poorly quantified in the context of VOICE, we decided to include them all in case some regions might consider some of them important.

It is worth mentioning here that all respondents to the questionnaires except for Cape Verde and Senegal adopted a national perspective on the requirements, capabilities, and data management. West Africa stands out in terms of their observing capabilities because of the inclusion of foreign (German and French) efforts. If this approach were to be applied consistently, the questionnaires would be filled in differently for most other regions. In general, there is a need to consider major international capabilities in the regions of interest and contrast them with the purely national ones.

Fisheries and biodiversity and ecosystems conservation rank first (**Figure 5**) among all societal observing objectives in each

[5]http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

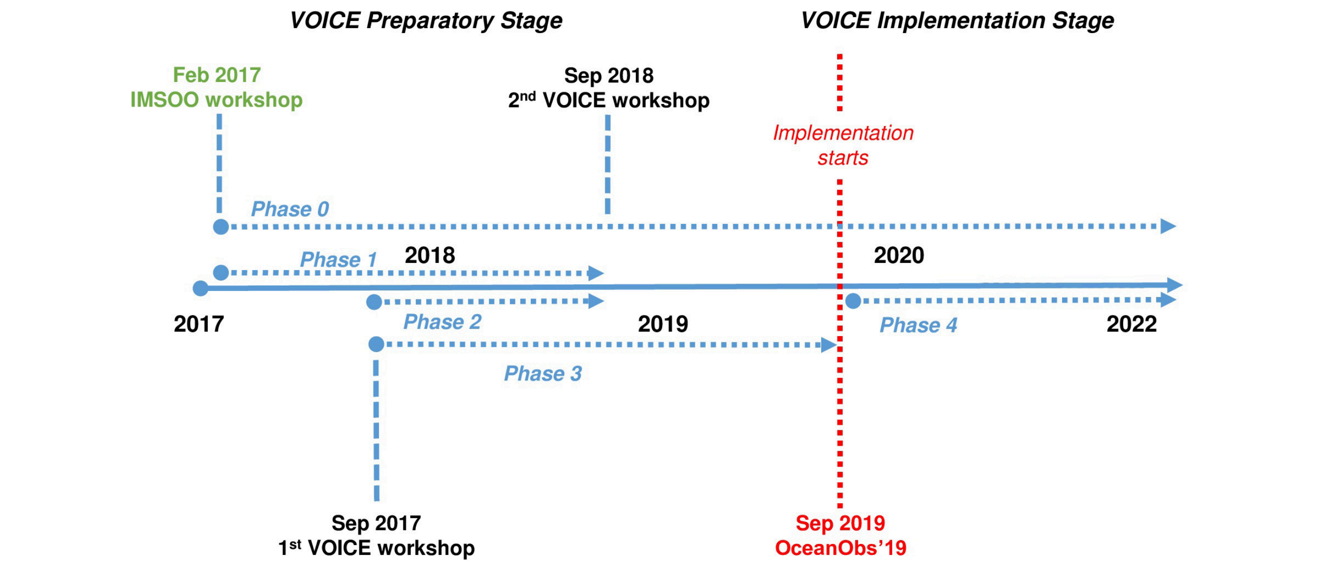

FIGURE 4 | The variability of the oxycline and its impact on the ecosystem (VOICE) timeline as agreed upon during the Integrating Multidisciplinary Sustained Ocean Observations (IMSOO) workshop.

TABLE 2 | List of questions in the questionnaires related to FOO1.

	Requirement setting processes (FOO1) in the questionnaire
Q1	What are the relevant societal impacts of changing OMZs that drive the investment in your regional observing system? *Fisheries, aquaculture, biodiversity, and ecosystem conservation, greenhouse gas emissions, and carbon sequestration were the proposed options with the possibility of additions*
Q2	What are the relevant societal benefits of changing OMZs that drive the investment in your regional observing system? *New genetic resource harvesting for industrial applications was the proposed option with possibility of additions*
Q3	What are the major motivations for observations in the region based on funded projects and how do they tie in with VOICE?
Q4	Are the societal and scientific requirements for your regional observing system in line with any of the VOICE specific questions listed below: *1. What are the processes that create and maintain an oxycline, its extent, and intensity?* *2. What are drivers for spatial (horizontal and vertical) and temporal variability of the oxycline from sub-diurnal to multiannual time scales?* *3. What are drivers in vertical extent, depth range, and intensity of the oxycline?* *a. Do mesopelagic fish/crustaceans/cephalopods affect the oxycline to an extent comparable with the role microbes have?* *b. What is the role of zooplankton diel vertical migration (DVM) on the oxycline?* *4. What are the impacts of oxycline variability in space or time on fish biomass, abundance, community structure, and susceptibility to fishing gears?*
Q5	Is there any historical data analysis and review of the literature aimed at developing a conceptual framework of the effects of the oxycline in your region?
Q6	What are the specific requirements (if any) set regarding essential ocean variables or other measurements? What are the measurements required to answer VOICE questions in your region?
Q7	What are some of the OMZ-related societal benefit data/information products needed in your region?

OMZ followed by aqua/mariculture. However, all OMZ regions stressed that fisheries were given the highest priority. The relative importance of other drivers (greenhouse gas emission, carbon sequestration, tourism, recreation and surfing, research and education, marine pollution from terrestrial waste (waste waters, plastics, nutrient loads), climate change, and ENSO varied among regions. The relevant societal benefits of changing OMZs that drive the investment in most of the regional observing systems are fisheries and ecosystem management and adaptation and for Ecuador the willingness to secure healthier environments for fisheries and aquaculture farming.

The term "fisheries" was generally used to mean both the population of a fish species occurring in a specific area or region, as well as the activities (e.g., catch, fleet dynamics) related to their harvest. Often, the specific area or region of interest is based on the life cycle and biology of the population, such as migration patterns of different life stages (e.g., eggs, larvae, juveniles, adults) and the degree of genetic mixing with other nearby populations of the same species. The fish and fisheries monitoring data are typically analyzed for the entire region or for subareas within the region and they indicate how the catch is reported (e.g., reporting zones) and how the fishery is managed (e.g., area closures).

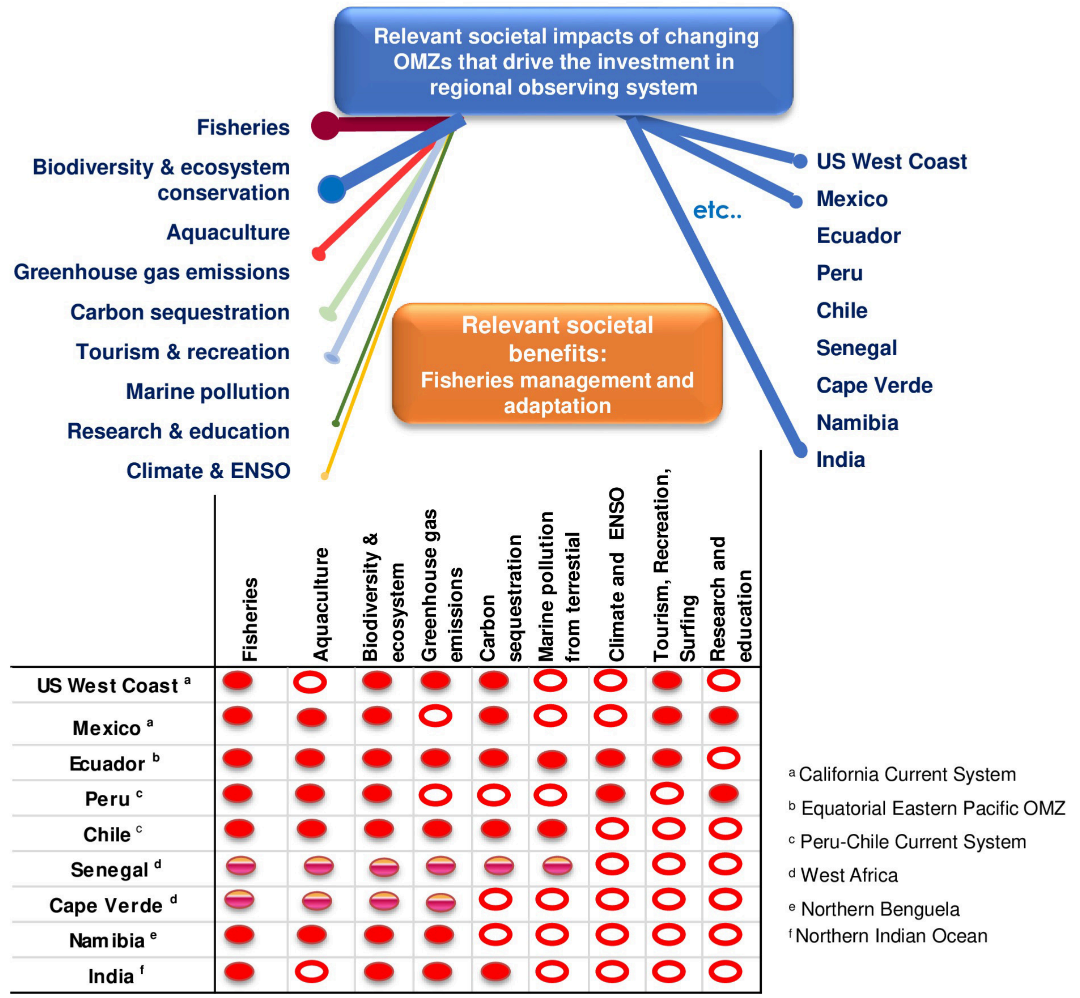

FIGURE 5 | Societal impacts and benefits are driving investments in a given oxygen minimum zone (OMZ) region of the world ocean. Shading indicates that these regions rely mostly on partnerships with foreign countries to carry out their monitoring activities. The two-toned pink oval indicates that the region relies mostly on partnerships with foreign countries, the filled red oval that the region is managing the monitoring at its own national level, and the outlined red oval that the region does not ensure the given monitoring activity. Please note it will not be repeated on all subsequent figures/tables.

Fish exhibit species-specific avoidance of low-oxygen areas (Craig, 2012). Individual fish are exposed to time-varying low oxygen concentrations because they are moving in oxygen fields that also vary in time and space (Neilan and Rose, 2014). Certain demersal fish species are able to live under the hypoxic conditions characteristic of OMZs, while others are not (Gallo and Levin, 2016). This exposure to low oxygen affects the growth, mortality, reproduction, and movement (as part of avoidance) of individuals (Wu, 2002; McNatt and Rice, 2004; Vaquer-Sunyer and Duarte, 2008; Thomas et al., 2015; Salvanes et al., 2018). If sufficiently high numbers of individuals are affected, the OMZs can lead to population-level changes in weight at age (growth), population size (total number of individuals in the region), and horizontal and vertical spatial distributions (Rose et al., 2009). Growth can affect mortality and reproduction (and therefore abundance) because these processes in fish are often strongly influenced by body size (Rose et al., 2001).

Some regions have well-established sustained national observing programs in coastal and open ocean waters, which operate all year at varying frequencies. Other regions rely to varying degrees on international partnerships through the Food and Agriculture Organization of the United Nations support, French IRD funding, and other projects (**Figure 5**).

With regard to the issue of the oxycline-related scientific questions (see **Table 2**) relevant in a given region, most regions answered positively to questions 1, 2, 3, and general 4 and Cape Verde to questions 3 and 4. All more general OMZ-related scientific questions relevant to study in the region (see the section "The Voice Initiative" above) were answered positively in all regions. This indicates that almost all EBS regions have relevant societal benefits and impacts of changing OMZs that drive their investment in their own EBS region.

A review of the literature reveals dedicated review papers on OMZs and ocean observing for some EBS regions, sometimes

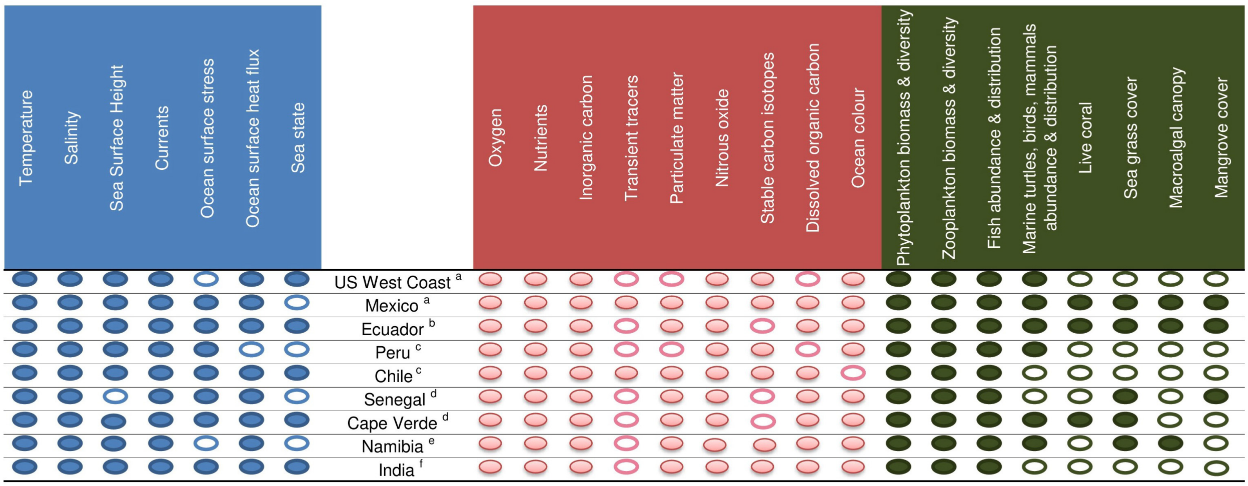

FIGURE 6 | Essential ocean variable observational requirements based on the questionnaire responses for each oxygen minimum zone (OMZ)-selected region.

in national scientific journals. Examples include, for instance, in the California Current system, works from Bograd et al. (2008, 2015), Keller et al. (2010, 2015, 2017), Koslow et al. (2011, 2013, 2017), Sato et al. (2017); in the Peru–Chile current system, Chavez et al. (2003, 2008), Gutiérrez et al. (2008), Ulloa and Pantoja (2009), Purca et al. (2010), Ulloa et al. (2012), Alegre et al. (2015), Graco et al. (2017); and in the Northern Indian Ocean, Naqvi et al. (2000, 2006, 2009), Prakash et al. (2012), Banse et al. (2014), and Bristow et al. (2017). Some of this research has focused on studying oxycline variability in a broader sense, examining ventilation processes of the OMZ at the basin scale but not encompassing all the VOICE objectives, thus being more focused on the climate observing objective and not on the fisheries objective. Certain review papers have taken a comparative approach to studying OMZ effects, for example, on benthic ecosystems and on demersal fish communities; these include data from many of the EBS (e.g., Levin, 2003; Gallo and Levin, 2016, and the related citations therein). It is also important to note the ongoing efforts by the International Union for Conservation of Nature in publishing a new global report on "Ocean deoxygenation: everyone's problem—causes, impacts, consequences, and solutions" and within the Intergovernmental Oceanographic Commission UNESCO working group Global Ocean Oxygen Network of a synthesis paper led by Grant Pitcher entitled "A comparison of ocean and coastal systems subject to low oxygen," which will include all our selected EBS regions. Some regions included a few manuscripts covering a historical analysis (e.g., Bograd et al., 2008; 2015; Koslow et al., 2011, 2013, 2017 for the California Current system).

Concerning the measurements of EOVs required to answer VOICE questions in a given region, **Figure 6** offers a summarized response. Physical EOVs like temperature, salinity, and currents are considered essential and should be measured as a function of depth in all regions. The same holds true for some biogeochemical EOVs such as oxygen, nutrients, and inorganic carbon. For biological EOVs, the monitoring of phytoplankton and zooplankton biomass and diversity are also critical as are fish abundance and diversity in all regions.

Ocean surface stress is thought to be critical for oceanic system dynamics in many of the systems. Sea surface height is indicated to be looked at almost everywhere. Sea state, a critical variable for air–sea exchange, is considered essential in many OMZ systems. Ocean color is used routinely in almost all regions. Particulate matter is not measured everywhere despite its key role in oxygen dynamics and carbon sequestration.

With regard to biological and ecosystem EOVs, information on upper trophic levels such as the abundance and distribution of marine turtles, birds, and mammals is considered a requirement by some questionnaire respondents in some regions but not all. It should be considered that our questionnaire process could have been subject to the presence of disciplinary bias, with insufficient attention paid to the monitoring of BioEco EOVs. Information on the requirement of higher trophic levels may not be present in the answers because the most knowledgeable people on the topic were not reached in our questionnaire and the communities of practices built around marine predators use different sampling platforms. A stronger interaction with these communities should thus be encouraged. Higher trophic levels are important in the VOICE context as indicators of marine ecosystem health, and although they are usually well documented, the data may not be easily accessible. Since fisheries rank as a top priority driver, we recommend a higher level of disaggregation in the future (e.g., demersal and pelagic fisheries) whenever possible.

Sea grass cover, macroalgal canopy, mangrove cover, and live coral are not estimated as essential everywhere, as their distribution varies widely, based on geographical and temporal requirements. However, for Mexico for instance, corals located at the fringe of the OMZ constitute a strong factor driving the need for investment and raising awareness of deoxygenation.

Other key variables, not yet considered as EOVs, such as microbes and iron, were also considered. Some regions answered positively to the questionnaire on these two variables, whereas others responded positively to only one of the variables.

Considering the synthesis of information regarding this FOO1 "Requirement Processes" illustrated in **Figures 5**, **6** and the master information, we can then attribute, somewhat subjectively, a range of levels within the mature, pilot, or concept readiness levels, considering the detailed description of each readiness level (UNESCO, 2012; **Table 1**). For instance, all regions were beyond the concept level, with six of them at levels 6–8, two at levels 4–5, and one at level 8. **Figure 7** presents the suggested allocation of readiness level assessment for all selected OMZ regions.

Coordination of Observing Elements: The Second FOO Pillar

The second FOO pillar (FOO2) sheet "Coordination of Observational Elements" seeks to answer the question "What do we (currently) measure, how and which coordination?" Here we are equally interested in learning about what phenomena are being observed and which parameters are being measured—both are closely linked to the scientific approach that has been selected in the FOO1. To assess the readiness level of FOO2, first a list of questions was formulated in the questionnaires (**Table 3**). The analysis was made by building a master answer file with all EBS regions and designing a graphical representation of the synthesized information (**Figures 8–10**).

It is important to note that answers to FOO2 questionnaires include observations which are project based (short lived) and national based (long term). Even if the sequence of project-based observing is almost continuous in some regions, this is still a gap in the system design because of all the contingencies (funding, asset sharing, etc.). It is then difficult from our questionnaires to firmly conclude on continuity of measurements over a decade or so for the selected OMZ regions.

Figure 8 provides a synthesis of all answers for the OMZ regions keeping in mind the mentioned caveats. What stands out is that the forcing mechanisms are well monitored using many of the physical EOVs, namely, temperature, salinity, wind stress, currents, sea surface height, and sea state, as are some of the biogeochemical EOVs (oxygen, nutrients). Riverine fluxes are addressed by three out of the nine OMZ regions. Regions offered quite distinct answers for biogeochemical and ecological phenomena. The US West coast documents all

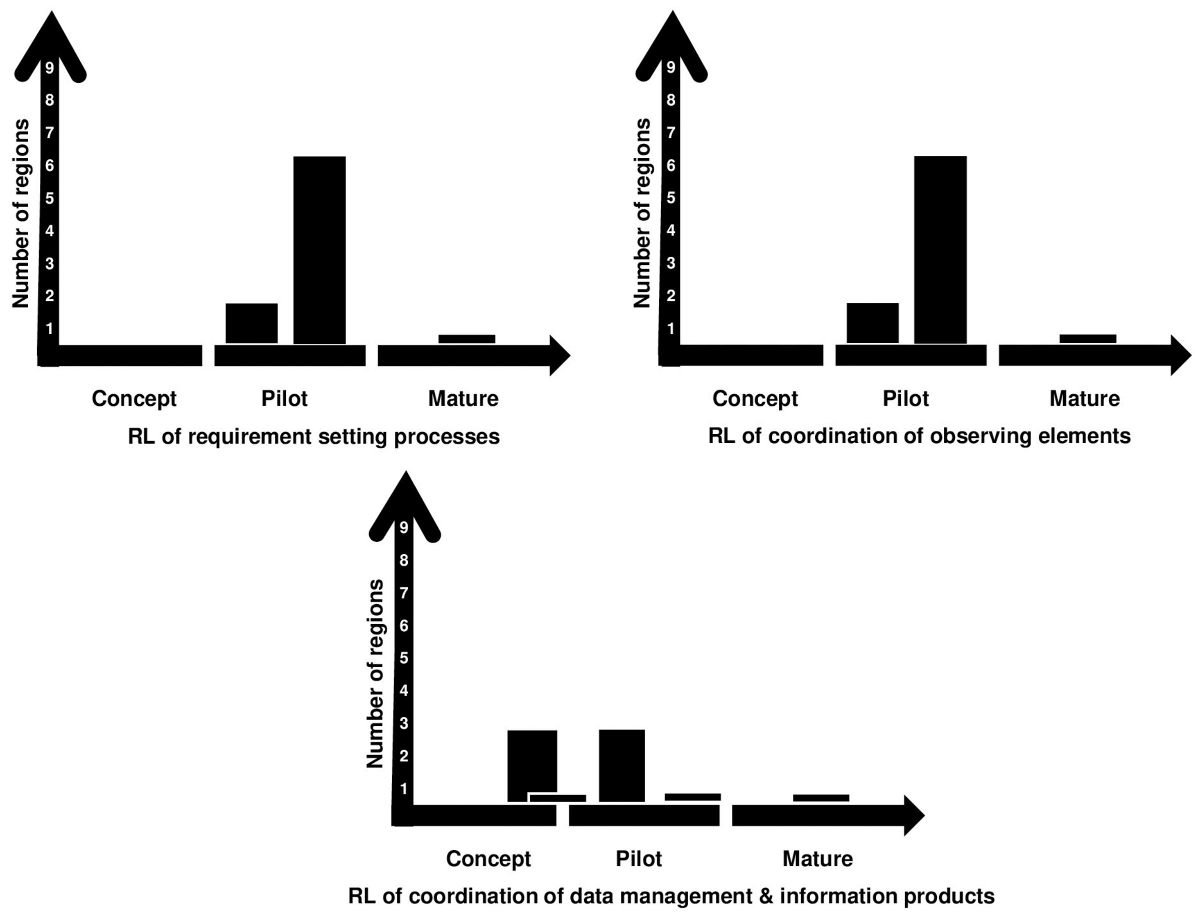

FIGURE 7 | Tentative assessment of readiness levels for Framework for Ocean Observing (FOO) pillars no. 1, 2, and 3 for all selected oxygen minimum zone (OMZ) regions.

TABLE 3 | List of questions in the questionnaires related to FOO2 and FOO3.

Coordination of observing elements (FOO2) in the questionnaire

Q1 What are some key processes/phenomena relevant to studying oxycline variability and its impacts on the ecosystem? Please mark those which are being observed in your region, or add any others, and indicate:

- *Forcing mechanisms (meso and sub-mesoscale features (physical and biogeochemical), riverine fluxes, upwelling dynamics, wind and waves, buoyancy forcing)*
- *Benthic-pelagic coupling (trophic connections, redox-dependent fluxes)*
- *Bottom-up effects (energy transfer, nutrient stoichiometry changes)*
- *Microbial ecology and metabolism (microbial community structure, anammox/denitrification rates)*
- *Physiological response to oxygen stress (fish biomass and community structure, fish habitats)*

Q2 What is the current status of EOV and any other key observations with respect to:

- *Which variables/parameters are currently being measured?*
- *Which platform(s) are they being measured on?*
- *What spatial coverage are they measured at? What spatial resolution are they measured at?*
- *What temporal frequency are they measured at? What instrument/sensor is being used to measure on a given platform?*
- *What is the method/technique used? What is the level of accuracy/uncertainty of a given measurement?*
- *What is the current modeling capability with respect to this EOV?*

Data management and information products (FOO3) in the questionnaire

Q1 What are the data management streams and information products available?
Q2 What is the regional dataset or information product available from the variable measurements, if any?
Q3 Is the data/information product freely available?
Q4 Is it obtained from single-platform observations or derived as a multi-platform synthesis product?
Q5 Is there quality control (QC) performed? If so, by whom?
Q6 Is the data available in near-real time? If so, by which stream?
Q7 What is the data repository?
Q8 Are there any relevant freely available modeling products available in support of observations?
Q9 Which phenomena (see **Figure 8**) do these data/information products inform about?
Q10 Who is the lead/contact principal investigator?

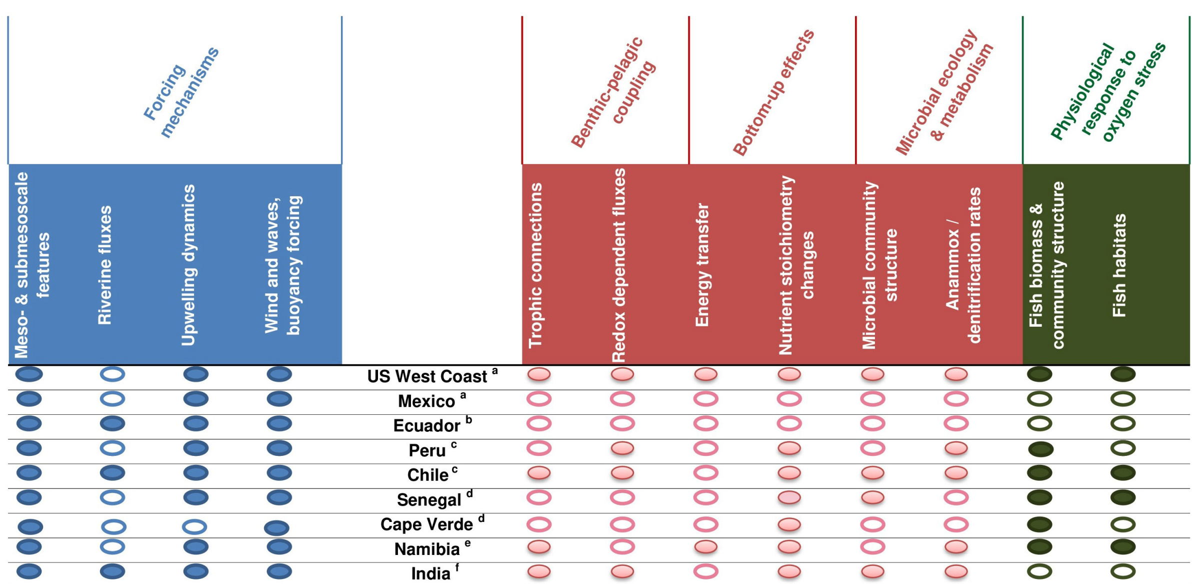

FIGURE 8 | Key phenomena relevant for studying oxycline variability and its impacts on the ecosystem as documented for each oxygen minimum zone (OMZ) selected region, and based on the questionnaire responses. Symbols as in **Figure 5**.

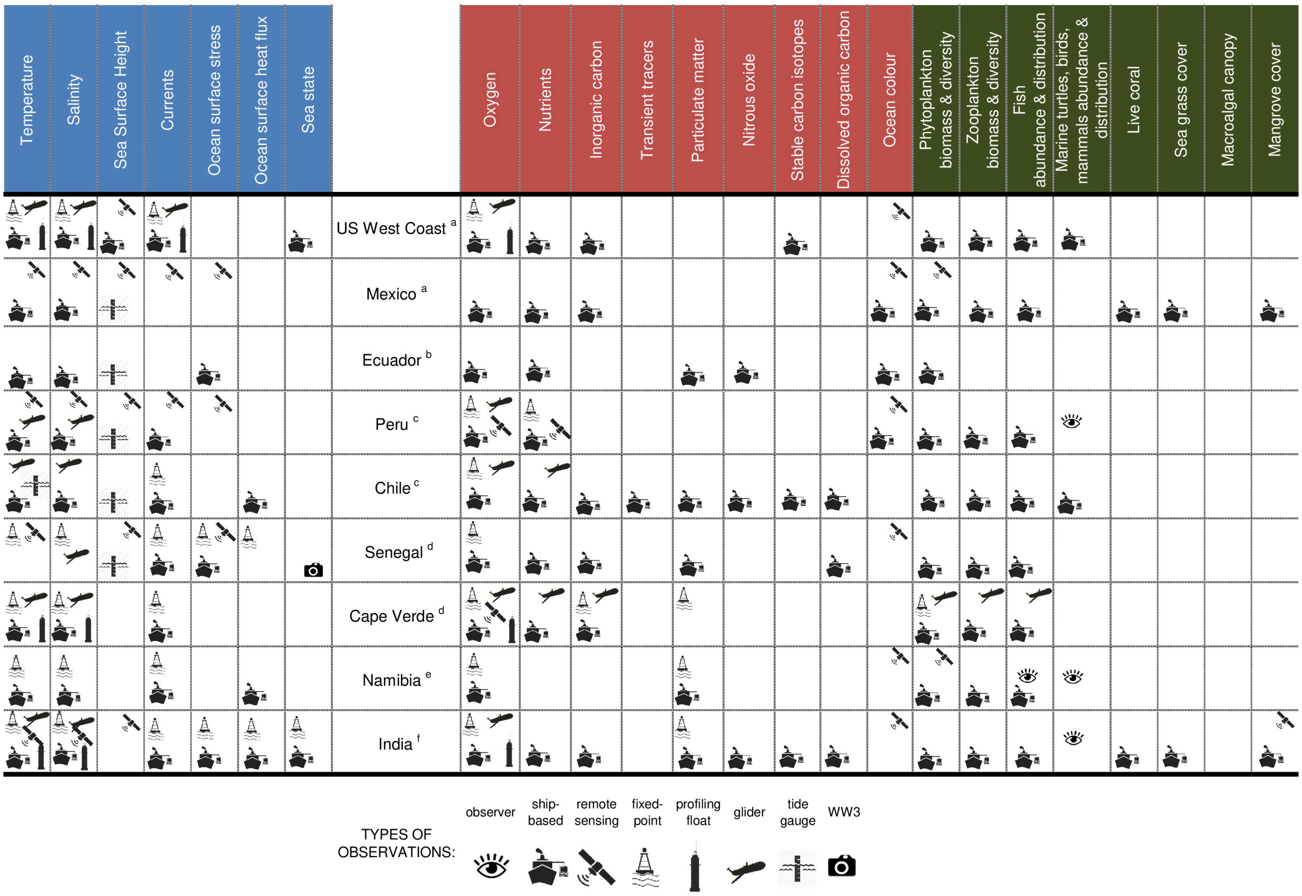

FIGURE 9 | Current status of essential ocean variable (EOV) measurements with respect to phenomena being monitored (see **Figure 8**) in all oxygen minimum zone (OMZ) regions. Different icons represent different observing approaches. Please note that the same symbol is used for hydrographic surveys and ships of opportunity lines (grouped under "ship-based"), one symbol for all: "fixed-point" observations (buoys, moorings), and one symbol for all "remote sensing" (airborne, satellite, etc.).

phenomena listed using many of the biogeochemistry, biology, and ecosystem EOVs. Many phenomena are covered in the Peru–Chile Current system, West Africa, and the Northern Indian Ocean, utilizing the basic EOVs, i.e., oxygen, nutrients, plankton, and fish biomass. Stable isotope work is used for trophic interactions investigations in the Northern Benguela Current System. Modeling work for food web studies and fish biomass and community structure is also carried out in the Northern Benguela and off West Africa.

Although fisheries rank first in the list of priorities of societal drivers, not all regions answered positively to fish habitat mapping with respect to oxygen levels and fish biomass and community structure.

Our challenge, and one of the objectives of VOICE, is to use ongoing and planned EOVs from ocean observing to characterize the oxycline in EBS regions and related changes in the temporal and spatial dynamics of the neighboring OMZ, with additional analyses and postprocessing to provide relevant information easily taken up by fisheries management. This will require both the ocean observing and fisheries science communities to change their ways of doing business. The ocean observing community will need to think about "looking up from beyond conventional EOVs to physical and biological features relevant to fish" as they pursue the analysis of observing data and merging it with other data streams (e.g., fish/fisheries monitoring data). The fisheries scientific community will need to be willing and receptive to "look down the food web to physics" to incorporate these new ocean observing products into their analyses that can then relate to management-relevant metrics. Such interdisciplinary analyses are feasible but will require a high degree of collaboration between the two scientific communities.

The second list of questions for the FOO2 intended to gather more detailed information on the observing platforms being used, which are a response to the spatiotemporal frequency of acquisition, coverage, etc., that are the result of the scientific approach selected in the FOO1. They are given in **Table 3**.

Figure 9 provides a list of platforms used in EBS regions. Some countries do not maintain moorings in their coastal or open ocean waters nor do they make use of autonomous vehicles. They use ship surveys, tide gauge networks, remote sensing, and ships of opportunity for monitoring the classical physical, biogeochemical, and biological EOVs. A few regions

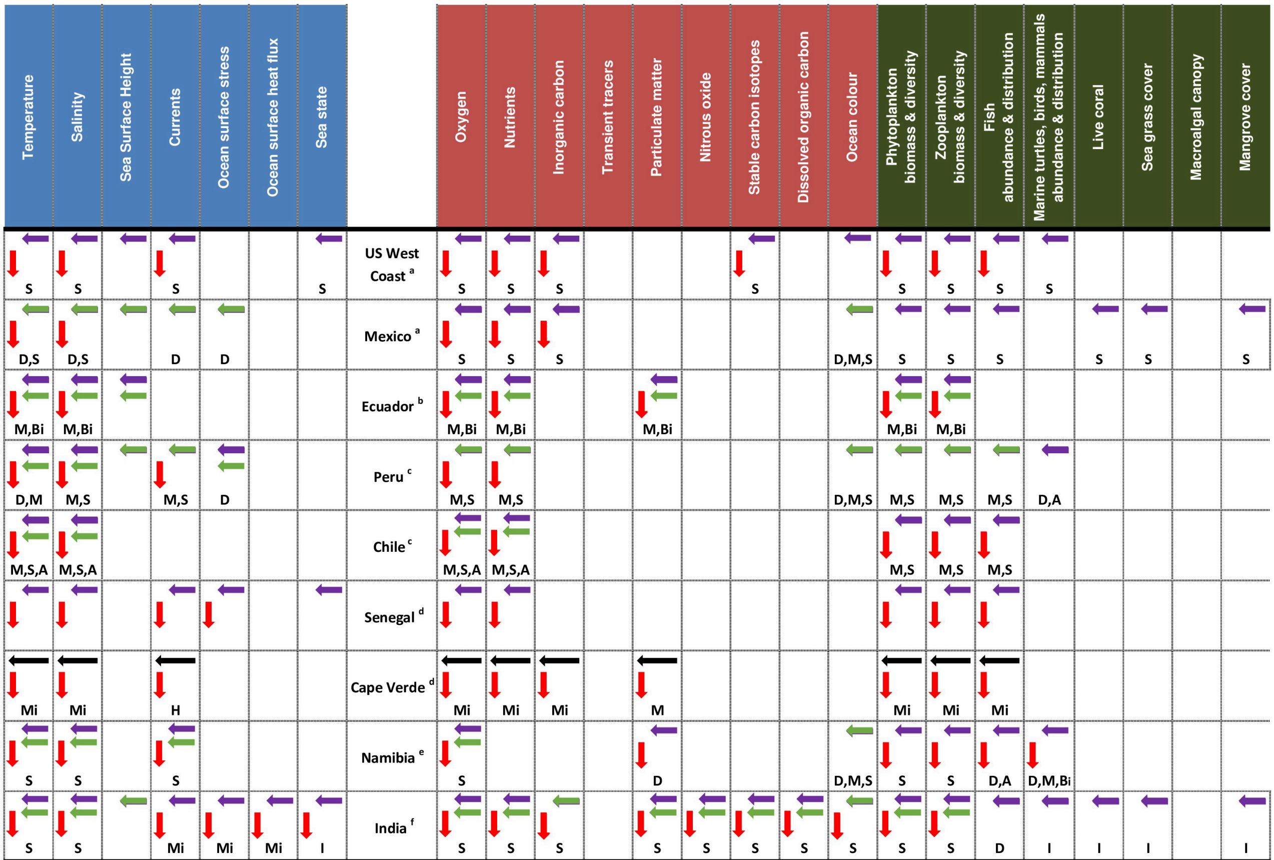

FIGURE 10 | Spatiotemporal resolution and geographical coverage of all essential ocean variables (EOVs) in the oxygen minimum zone (OMZ) regions. Definition of symbols used: A annual, Bi biannual, S seasonal, M monthly, W weekly, D daily, H hourly, Mi minutes, and I irregular. Arrows indicate: mesoscale (black), regional (green), coastal (purple), depth (red).

use a wide variety of platforms, including moorings, ships, and autonomous vehicles such as buoys, gliders, and floats, and remotely sensed data for covering a large number of EOVs. Some regions have multidisciplinary moorings addressing physical and biogeochemical EOVs and use autonomous technologies for both physical and biogeochemical EOVs. Almost all regions mention the use of satellite information.

All Pacific regions and Senegal off West Africa deploy and maintain tide gauges. Senegal uses cameras on their shores to document sea state. Ecuador is systematically using ships of opportunity. Overall, the physical EOVs are well documented; the situation is slightly different for biogeochemical EOVs: oxygen, nutrients, inorganic carbon, particulate matter, and ocean color are the most covered, but for biology and ecosystem EOVs, only plankton biomass and diversity as well as fish abundance and distribution are covered. Our questionnaire results suggest that top marine predators are less surveyed, and live coral, mangrove, and sea grass cover are rarely surveyed; however, additional surveys may be ongoing that are not known to the participants of the VOICE group.

Regions employ different strategies for observation of EOVs in space and time providing varying resolutions (**Figure 10**). Some regions perform regular seasonal surveys for many of the physical, biogeochemical, and ecological EOVs. Others tend to show higher frequency in monitoring; some physical EOVs are measured daily or even more frequently on moorings. Other regions go down to a monthly frequency, for physical, biogeochemical (oxygen, nutrients, inorganic carbon, particulate matter), and biological (phytoplankton, zooplankton, and fish) EOVs. Some countries perform only coastal surveys, whereas others combine coastal and open ocean surveys. **Figure 10** cannot be considered as a reliable picture of national sustained observations in all EBS regions due to the limitations of the questionnaire design mentioned earlier. Project-based observing may be designed to address specific scientific questions on a couple of year time scale, setting, for instance, the choice of platforms/sensors and spatiotemporal resolution. Observing efforts in some regions include international capabilities so the overall picture might not entirely reflect the national potential for truly sustained multidisciplinary observations set to address the original requirement. This variability points to the needs to understand the observing system methodologies and uncertainties. Where "Best Practices" (Pearlman et al., 2017, 2019) can be used, the comparability of measurements can be significantly improved. Broad propagation and adaption of best practices methodologies can address this.

Considering the synthesis of information regarding this FOO pillar on coordination of observation elements as illustrated in **Figures 8–10** and the master information, we can then empirically attribute a range of levels within the mature, pilot, or concept readiness levels, considering the detailed description of each readiness level (UNESCO, 2012; **Table 1**). For instance, all regions exceeded the concept level, with six of them at levels 4 and 5, two at level 4, and one at level 8. **Figure 7** presents the suggested allocation of readiness level assessment for all selected EBS regions.

Data Management and Information Products: The Third FOO Pillar

The third FOO pillar (FOO3) "Data management and information products" seeks to summarize "How are the data managed, integrated, and converted into ocean products?" This entails stating raw data and information product availability to the public, quality control (QC) protocols, data repositories, etc. As the outputs of the framework, data and information products will be the interface for most users. Ocean information products are required to support decision making in diverse areas such as climate studies and adaptation, disaster warning and mitigation, commerce, and ecosystem-based management. Although the product-based verification of how well the initial requirements are met is theoretically a good approach, we cannot assess this feedback here for lack of sufficient information on the information products or how comprehensively they were treated in the questionnaire. Here, we simply synthesize the listed information products (fish stock assessments, model forecasts, climatologies, etc.) mentioned in the EBS regions keeping in mind that we are not closing the loop from scientific outputs to ecosystem services and that such a product-based verification should be the next step to be carried out within the regions.

The participants were asked to identify the existing raw data collected and/or information products derived from data and used by stakeholders in connection with the issue of changing OMZs and the impact on EBS in the VOICE context, grouped by EOVs or other key measurements performed in the region. For each product, it was requested that the availability to the public, QC protocols, and data repositories be identified. Only EOVs and their data products that exist in the region and which are (or could be) of relevance to VOICE are to be mentioned.

Figure 11 depicts the main answers to the list of questions in **Table 3** for FOO3. The low number of database repositories with free access and, in some cases, the inadequate application of standardized QC procedures for data management of certain EOVs should be noted. Some regions offer data availability upon request for many EOVs, either physical, biogeochemical, or related to biology and ecosystems. Few regions measure all EOVs, apply the appropriate QCs, and make the data freely accessible. For physical EOVs such as temperature and salinity, almost all regions perform QC exercises. Currents, wind stress, and sea state are rarely quality controlled, and

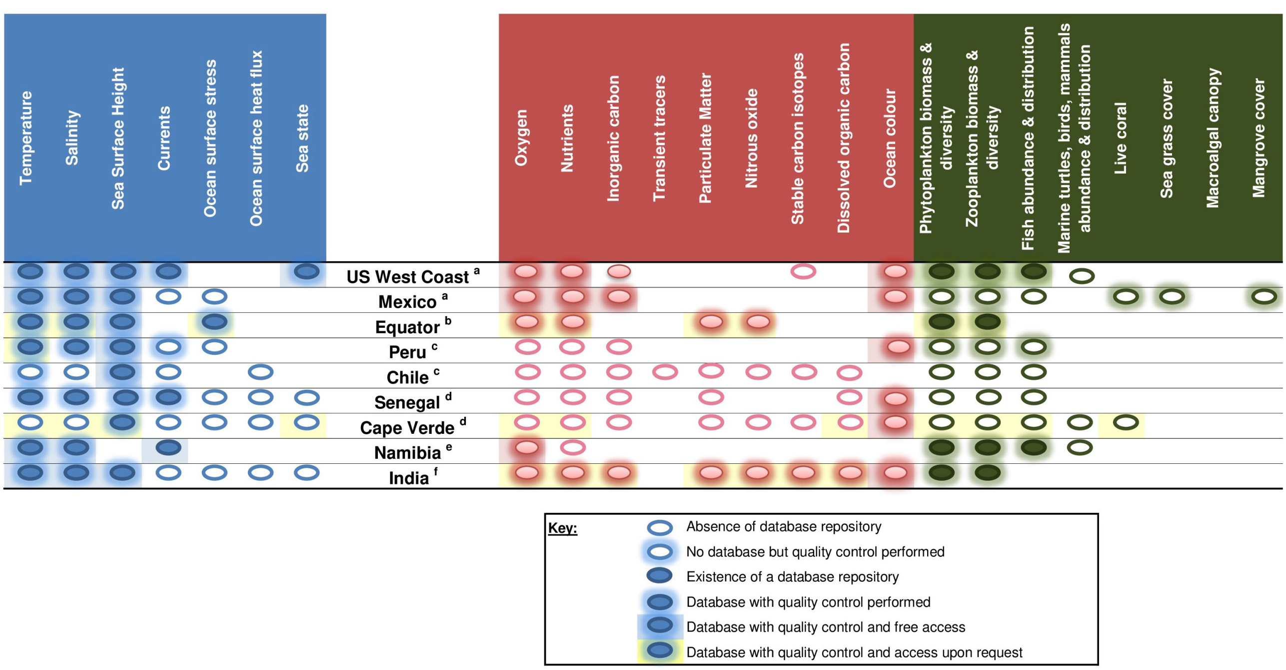

FIGURE 11 | Current status of data management and information product delivery with respect to essential ocean variables (EOVs) in the oxygen minimum zone (OMZ) regions participating in the readiness level assessment.

very few databases exist. About half of EBS regions apply QC measures on biogeochemical, biological, and ecosystems EOVs. Remotely sensed data such as sea surface height and ocean color are usually well utilized since these databases are open access. Upper trophic levels, live coral, macroalgal canopy, seagrass, and mangrove covers are the least monitored and seem not to be archived in any database. However, there are likely more activities related to variables that our questionnaire did not capture, for instance, the fisheries databases for large pelagic fish compiled by several regional fisheries management organizations (RFMOs) whose areas of competence encompass the EEZ part of the OMZ in studied EBS regions.

With respect to information products listed in the questionnaires, some regions have produced either data climatologies (Peru, Namibia), parameter maps, data visualization tools, time series or parameter sections and figures, and indices (US West Coast, Peru, Cape Verde, and Namibia) and make modeling results available (Senegal, Namibia).

Considering the synthesis of information regarding the FOO3 on data management and information products as illustrated in **Figure 11** and the master information, we can then empirically assign a range of levels within the mature, pilot, or concept readiness levels, considering the detailed description of each readiness level (UNESCO, 2012; **Table 1**). For this FOO3 pillar, all regions were spread from levels 3–8. **Figure 7** presents the suggested attributed readiness level assessment for all EBS selected regions. Considering the three broad categories of FOO pillars (concept, pilot, and mature), our EBS regions fall into either the pilot or mature categories for the first two pillars, whereas for pillar FOO3, the distribution of EBS regions ranges from concept to pilot to mature categories. These assessments are tentative because they were based on the information provided by targeted individuals and not based on any comprehensive survey of all observing system managers and stakeholders.

RECOGNITION OF GAPS

We undertook the first readiness level assessment of ocean observing for OMZ/EBS guided by the observing strategy as outlined in the FOO. Our assessment is an initial step toward recommendations for a fit-for-purpose ocean observing system capable of providing key information products and informing society about various observing objectives related to the variability of the oxycline and its impact on the marine ecosystem in EBS. Some caveats and precautions have been put forward in FOO *Readiness Level Assessments in VOICE Regions* related to the task of defining and assigning the readiness level for the FOO pillars.

Our questionnaire process likely presents a disciplinary bias, in that insufficient attention was paid to the monitoring of certain biology and ecosystem EOVs. These include turtle, bird, mammal abundance, and distribution EOVs, fish EOVs, or habitat type EOVs, in which cases regional champions often did not manage to consult with specialists in the field. This is true despite the fact that all regions identified fisheries as their primary ocean observing objective. This bias is particularly important to note in the case of higher trophic level species as they constitute key indicators of marine ecosystem health. Future assessments should ensure wider consultation with local experts, RFMOs, and international networks, such as the Climate Impacts on Oceanic Top Predators—a regional program of the Integrated Marine Biosphere Research.

The selected OMZ regions responded individually to the questionnaire for fish abundance and distribution EOV. For large pelagic fisheries, the Secretariats of the tuna RFMOs, namely, WCPFC (West Pacific), IATTC (East Pacific), ICCAT (Atlantic), and IOTC (Indian) compile catch, effort, and size data provided by the national administrations on the basis of scientific sampling. Commercial fisheries data are available in aggregated format (1° or 5° spatial grid) through these RFMOs. High-resolution information is held in national databases but is not available for public use. Exchange agreements may have to be negotiated for access to these data. This may explain the lack of integration of oceanographic data from oceanographic programs with fisheries including biological and environmental data. These RFMOs may lack the purely oceanographic and biogeochemical expertise. Initiatives are under development in ICCAT and IOTC toward ecosystem assessments incorporating biophysical interactions (Juan-Jorda et al., 2018a,b). Added expertise based on the integration of relevant sustained oceanographic observations would be very welcome by these stakeholders.

The issue of linkages between the three FOO pillars appeared to be a major weakness of the overall FOO concept making the readiness level assessment individually for each pillar a challenging task.

The gaps identified during this study varied but included gaps in the design of the questionnaire and survey itself, the observing network itself, a lack of communication between national agencies, or limitations in the use of data for public distribution and the lack of public distribution of important data; all of these contribute to not fulfilling elements of the overall ocean observing value chain. Certainly, our *ad hoc* designed questionnaire (**Tables 2**, **3**) and likewise the execution of the survey would very much be improved by following strict protocols (Burns and Kho, 2015; Krosnick, 2018) and consulting with social science experts not represented in the VOICE group.

Gaps in Questionnaire/Survey Design and Analysis

The accuracy of a questionnaire depends on the quality of questions chosen and distributed to the respondents, namely, structured versus open questions, instructions with the survey questionnaire, short and concise questions, unbiased questions, questionnaire should undergo pilot testing, limitation of both response and non-response bias, unbiased and representative sample of the respondents population, and assessment of the clarity and transparency of the reporting of the survey results. We acknowledge that our approach has inherent weaknesses since it did not comply with the previously cited protocols. All authors decided to merge the analysis that could be done on each region. This might be an additional weakness of the analysis since maturity levels vary depending on regional capabilities and including differences or similarities across regions and how these gaps affect the readiness levels within FOO pillars for OMZ regions could improve the process for the development of the VOICE network.

Gaps in Requirement Processes

Fisheries and ecosystem management were identified as a highly relevant ecosystem service and societal impact of (changing) EBS in all of the study regions surveyed, as was biodiversity and ecosystem conservation. These activities often occur together and, in some situations, can interfere with each other when their activities overlap with shared species or in space.

Gaps in Coordination of Observation Elements

A lack of secured funding for observations impairs the sustainability of observing systems. It was recognized by the responses to questionnaires that a large uncertainty about ship access exists, the most important observing platform according to the questionnaire. This uncertainty varies of course according to regions, but it seems a robust risk. Currently, research ships are often not properly maintained or too costly to rent by research institutions and there are issues with ship management and sometimes ship equipment.

Wind stress is important in EBS and also a critical factor in oxygen dynamics, but it is not monitored everywhere. However, satellite information could be more widely used as wind stress products tailored for coastal applications now exist. The wind products are able to provide information on coastal winds, including the wind drop off close to the coast in upwelling regions.

The observing capacity for the particulate matter EOV is not fully developed. Ships of opportunity are only considered a valuable platform by Ecuador. Another major gap is the lack of sampling efforts on the seafloor/benthos compared to the pelagic zone. Benthic processes are also important in considering the oxycline. For example, the oxycline frequently shoals nearshore, and in areas with shallow OMZs, inner shelf dynamics may affect the oxycline.

As pointed out above, further integration of fisheries-related observations with oceanographic data from oceanographic programs is needed and planned. A pathway for information flow to link OMZs to EBS fisheries has yet to be developed to allow appropriate measurements of oxycline variability to be integrated with existing fish monitoring data (fishery-independent surveys that include biological, acoustic, and oceanographic observations), with fisheries data (catch, vessel trips), fishing vessel logs and acoustics data, and available process data (e.g., behavior from tagging, laboratory experiments on effects of low oxygen) for fish species of interest.

The observing networks that coordinate the technical and data aspects of the observing platforms promote and encourage the creation of standard operation procedures (SOPs) and manuals that are considered "Best Practices" in the respective community. Many SOP/manuals are available for almost all platforms, variables, and sensors,[6] but a community-accepted recommendation is often missing. Because the observing networks best know their technology, they are tasked with providing the QC and quality assurance (QA) of the data. However, it should be mentioned that even in cases where no QA/QC has been applied to data, the integration process can enable a second QA/QC from the intercomparison of data, which is part of the third FOO pillar.

There is also a significant gap in the interoperability of data and its processing. The identification of best practices and methodologies that can be offered to and then adopted by the regional observing programs will impact both the observation quality and end products. Consistent QA/QC will also help to understand the uncertainty and real variability of observation data. Best practices in QA/QC, and more generally in observation and archiving techniques, are "available" but not easily accessible because they are scattered across the web or in diverse repositories.

Gaps in "Data Management and Information Products"

The third FOO pillar requires the largest human resources input to increase readiness levels in EBS regions (**Figure 7**). For the Angolan EBS, Tchipalanga et al. (2018) demonstrate how capacity development combined with a release of observational data can create new ocean observing products. The existence of databases, application of standardized QC procedures for real-time data, and development of data repositories or increased accessibility of data repositories are critical issues. Routes to be followed in addressing these issues will have to be discussed and agreed upon, considering national budget and staff constraints and varying policies but also international opportunities and cooperation.

There is presently no simple and direct connection between the Food and Agriculture Organization and GOOS databases. Fisheries management can be complicated and is typically species and region specific, but there are several metrics that widely resonate with fisheries management (Hilborn and Walters, 2013). These include weight at age (reflects growth), fecundity (egg per individual by age or size), recruitment (annual number surviving from eggs and larvae to a predetermined size, age, or date), natural mortality rate, and a quantity termed "catchability" that relates sampled densities of individuals (e.g., number per tow) to the number of individuals in the stock. Although there are several encouraging examples of OMZs (e.g., US West coast, Northern Benguela, Peru–Chile Current system) information being linked to fisheries and fisheries management processes (Rose et al., 2019), oxycline variability, along with other environmental parameters, is not

[6] See https://www.oceanbestpractices.net/.

quantitatively used for developing stock assessment estimations and for the management decision-making process, for most of the VOICE regions.

The lack of standard procedures and best practices for data methods and QC is a barrier to releasing and integrating data for many regions.

Marine aquaculture was also among the top societal drivers in the responses to our questionnaires. It is a rapidly growing sector responding to the need to feed a growing global population. Sea ranching techniques range from fattening tuna in pens off Mexico to growing scallops in Tongoy Bay, Chile. Since aquaculture relies on raising animals in fixed locations, and often deals with high densities of animals, oxycline variability, affecting oxygen and pH conditions, can be an important concern. As aquaculture continues to grow, there will be opportunities to further incorporate data collection on EOVs relating to the oxycline in EBS regions, as well as developing management strategies that make use of data products from existing observational systems. This is a good example of an important societal impact of our work.

CONCLUSION AND RECOMMENDATIONS

Building on the FOO strategy, we present a readiness level assessment for multidisciplinary ocean observing to monitor a key parameter, the upper oxycline, in highly productive and economically important EBS that neighbor the major OMZ of the world ocean, namely, the US West coast, the Southern California Current system off Mexico, the Equatorial Eastern Pacific off Ecuador, the Peru–Chile Current system, West Africa off Senegal and Cape Verde Islands, the northern Benguela off Namibia, and the Northern Indian Ocean (Bay of Bengal, Arabian Sea).

The assessment was executed as a major contribution to an anticipated end product of the VOICE initiative—a blueprint for a multidisciplinary and sustained ocean observing system in economically important EBS regions. A prerequisite for optimization is the disclosure of the observing efforts and other elements of the ocean observing value chains in the EBS regions. An *ad hoc* questionnaire was designed and distributed to scientists and stakeholders of selected EBS regions. Both the design of the questionnaire and the selection of stakeholders are open to substantial improvement, e.g., by consulting experts in survey design and execution. Regional champions were identified for the VOICE regions that provided input addressing all the value chain/FOO elements: requirement processes, coordination of observational elements, data management, and information products. The questionnaire responses revealed a variety of observing requirements linked to the variability of the oxycline and its impacts on the ecosystem in EBS regions. An assessment of readiness level for existing observing, data availability, and integration is provided and synthesized to inform local, regional, and even global stakeholders. We found that an observing strategy for fisheries and ecosystem management exists in all EBS regions, but maturity levels and observation capabilities differ. The readiness level for the VOICE elements is derived for the regions and points at system weaknesses. A major weakness is the difficulty to easily connect fisheries-related data and oceanographic databases. Potential routes for developing strategies for readiness level improvements include the need to provide interoperable oxygen and other environmental data that are colocated with fisheries data in space and time so they can be easily taken up in the fisheries management process and also by the marine aquaculture sector. The feasibility of such interdisciplinary analyses will be key to the optimization of the ocean observing value chains in the upwelling EBS regions.

Some immediate recommendations based on the assessment that will enhance ocean observing value chains in OMZ neighboring EBS regions include (in no particular order):

- Develop strategies to connect ocean observing design to social scientists, economists, industry, and other groups at regional (up to EEZ of respective EBS) and global scales to perform proper readiness level assessments. In an ideal world in each region, this could be achieved through a carefully designed survey, dedicated regional workshops with all key actors present (including scientists from the physical, biological, biogeochemical oceanography and biodiversity sectors, fisheries scientists, relevant stakeholders) and in defining either a target population of respondents or selecting a sample representative of the respondent population. The key is to bring together multiple end users of the ocean to make informed and coordinated decisions about identifying where and how an ocean area is to be used for which goal and which resources.
- Greatly enhance capacity building development in EBS regions to unlock new opportunities for data use and data integration, such as the use of remote sensing as an easy way to foster the use of satellite data.
- Provide access to and training for customized regional ocean products for the obvious benefits of regional ecosystem analysis but likewise to increase the acceptance and willingness to support and engage in ocean observing (e.g., ocean observation devices on fishing boats).
- Modify fish surveys to account for possible effects of the oxycline and ensure that fish surveys include measurements of other parameters typically measured for EBS observing. The vertical discontinuity of echotraces as recorded by research echosounders onboard scientific and fishing vessels can serve as a proxy of the oxycline depth providing high-resolution data of fish school abundances and habitat compression by the oxycline (Bertrand et al., 2011). If one can merge all available datasets together, more knowledge can be gleaned for the system under study. Oxygen and other environmental conditions can then be considered in the stock assessments in EBS regions and the information taken up to inform fisheries management.
- Enhance the observing capacity for the particulate matter EOV by deploying more sediment traps on moorings. However, these require regular servicing and tend to integrate observations over time. Other options are to record particulate backscattering or beam attenuation with sensors implemented on the Biogeochemical Argo

floats and/or to measure particulate organic carbon concentrations using Niskin bottles during ship surveys. Remote sensing algorithms for measuring particulate organic carbon perform poorly in upwelling regions and greater attention should be focused on improving them.

- Encourage all EBS regions to consider ships of opportunity as a valuable platform as is done by Ecuador. All regions could benefit from deployment of Expendable Bathythermographs on commercial shipping lanes to obtain temperature profiles of the top 400, 800, or 1500 m of the water column. Since some commercial lanes follow the South American and African coast lines, some regions, e.g., Peru and Chile, and Senegal and Namibia could share the instrumentation to be set up on board. This will feed predictive coupled models with regular observations, thus improving their forecast capacities.
- Sustain and constantly improve routine observing efforts (e.g., satellite missions) and downstream services, e.g., as provided in Europe by the "Copernicus Marine Environment Monitoring Service."[7]
- Foster more international collaboration, especially when crossing EEZ waters. For instance, within the auspices of the GOOS Regional Alliance for the South-East Pacific region, scientist exchanges occur, but the sharing of methodologies, protocols and best practices, raw data, and the intercalibration of sensors remains to be done. The first step would be to link the scientists to the globally coordinated observing networks and to encourage use of the IODE OceanBestPractices System[8] (Pearlman et al., 2019).
- Include in future VOICE-type multidisciplinary ocean observing assessment a wider community of scientific experts (higher trophic level species as key indicators of marine ecosystem health to fully account for Biology and Ecosystems EOV observing efforts in the EBS regions).
- Improve the interoperability of data by adopting the Findable, Accessible, Interoperable, Reusable[9] data principles and motivate for the exchange and implementation of common methods in observations and data processing. It is recommended that best practices for the OMZ/EBS be contributed to the OceanBestPractices System.
- Launch a pilot implementation project motivated by the local observing objectives, with a partnership of EBS neighboring countries and relevant service providers and capacity developers, and considering VOICE recommendations.
- Initiate and support routine review of the ocean observing value chain activities in the EBS regions by evaluating primary activities: (i) requirement setting process, (ii) coordination of observation elements, and (iii) data management and information products; and secondary activities: research and development, and human resources. Such an evaluation process could include a science and implementation committee that oversees the adequacy of the scientific approaches used and ensures a seamless link between scientific assessment and information product delivery (e.g., as in the case of the large marine ecosystems or the International Council for the Exploration of the Sea).

AUTHOR CONTRIBUTIONS

VG, JK, AP, MT, JP, FC, TK, LL, WN, KR, KW, and FM conceived the VOICE initiative. VG, JK, AP, and MT designed and conducted the questionnaires and analyzed the results. TA participated in the responses to questionnaires analysis. DG, LL, NG, BM, IM, WN, GP, DS, EP, MV, BF, HM, MH-A, AV, OP, and MC-D'O provided information in response to the questionnaires. All authors discussed about the questionnaires results and reviewed the manuscript.

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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.2019.00722/full#supplementary-material

[7]http://copernicus.eu/main/marine-monitoring
[8]https://www.oceanbestpractices.org/
[9]https://www.go-fair.org/fair-principles/

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frontiers in Marine Science

REVIEW
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ILTER – The International Long-Term Ecological Research Network as a Platform for Global Coastal and Ocean Observation

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Understanding the threats to global biodiversity and ecosystem services posed by human impacts on coastal and marine environments requires the establishment and maintenance of ecological observatories that integrate the biological, physical, geological, and biogeochemical aspects of ecosystems. This is crucial to provide scientists and stakeholders with the support and knowledge necessary to quantify environmental change and its impact on the sustainable use of the seas and coasts. In this paper, we explore the potential for the coastal and marine components of the International Long-Term Ecological Research Network (ILTER) to fill this need for integrated global observation, and highlight how ecological observations are necessary to address the challenges posed by climate change and evolving human needs and stressors within the coastal zone. The ILTER is a global network encompassing 44 countries and 700 research sites in a variety of ecosystems across the planet, more than 100 of which are located in coastal and marine environments (ILTER-CMS). While most of the ILTER-CMS were established after the year 2000, in some cases they date back to the early 1900s. At ILTER sites, a broad variety of abiotic and biotic variables are measured, which may feed into other global initiatives. The ILTER community has produced tools to harmonize and compare measurements and methods, allowing for data integration workflows and analyses between and within individual ILTER sites. After a brief historical overview of ILTER, with emphasis on the marine component, we analyze the potential contribution of the ILTER-CMS to global coastal and ocean observation, adopting the "Strength, Weakness, Opportunity and Threats (SWOT)" approach. We also identify ways in which the *in situ* parameters collected at ILTER sites currently fit within the Essential Ocean Variables framework (as proposed by the Framework for Ocean Observation recommendations) and provide insights on the use of new technology in long-term studies. Final recommendations point at the need to further develop observational activities at LTER sites and improve coordination among them and with external related initiatives in order to maximize their exploitation and address present and future challenges in ocean observations.

Keywords: climate change, marine ecosystems, ecology, EOVs, SWOT, DEIMS

INTRODUCTION

Human activities threaten both the natural functioning of coastal and marine ecosystems and their sustainable use by present and future generations (Worm et al., 2006; Defeo et al., 2009; Halpern et al., 2012; Howes et al., 2015; Drius et al., 2016; Malavasi et al., 2018). Developing and delivering the ecological knowledge necessary to quantify how threats to coastal ecosystems impact national and international economies, policies and the sustainable use of the sea poses a significant challenge. Gaining such ecological knowledge on a local scale requires long-term observations of both environmental and biological variables, such as temperature and species richness. Effective assessment, management and prediction at the global scale, however, requires infrastructure and ecological observatories capable of systematically integrating from a long-term, large-scale, and whole-system perspective. Developing new observing systems and strengthening existing initiatives in a coordinated, standardized, global effort is essential to address these challenges.

Marine observatories provide the infrastructure and logistical support necessary to acquire data and knowledge for these purposes. The Global Ocean Observing System (GOOS[1]) was established to provide a sustained, collaborative system for ocean observation that brings together *in situ* networks, remote sensing systems, government stakeholders, UN agencies and individual scientists. An important outcome of OceanObs'09 was the recognition of an imbalance between physical and biogeochemical/biological/ecological observations within most observing systems and the recommendation that GOOS consider how to expand the scope of observations to best address socially pressing global issues, including food security, harmful algal blooms, the spread of dead zones, and biodiversity conservation (Lindstrom et al., 2012). To that end, GOOS has established Biology and Ecosystem Essential Ocean Variables (EOVs[2], Miloslavich et al., 2018). The International Long-Term Ecological Research Network (ILTER[3]) is uniquely poised to contribute to the need for integrated, global observation of biological and ecological aspects of coastal ecosystems. Focal areas of the ILTER coastal and marine sites (henceforth ILTER-CMS) include: the consequences of biodiversity alteration for ecosystem functioning and services, documenting productivity changes, and understanding the cumulative impacts of multiple stressors including overfishing and ocean acidification. In this paper we explore the coastal and marine component of ILTER as a platform for global coastal and ocean observation, highlighting the role of ecological observations to address the challenges posed by climate change and evolving human needs and stressors within the coastal zone. To begin, we provide a brief historical overview of ILTER and describe its organization, with emphasis on the marine component. Next, we analyze the potential contribution of the ILTER marine component to global coastal and ocean observation adopting the "Strength, Weakness, Opportunity and Threats (SWOT)" approach. From this analysis, we elaborate on two specific opportunities for ILTER-CMS to contribute to global ocean observing. One, we identify ways that the *in situ* parameters collected at ILTER sites fit within the EOVs framework, as proposed by the "Framework for Ocean Observation" (FOO, Lindstrom et al., 2012) recommendations, and, two, provide insights on the use of new technology in long-term studies. Finally, we recommend paths forward to address future challenges.

HISTORICAL PERSPECTIVE AND OVERVIEW OF ILTER

The ILTER was established in 1993, 13 years after the launch of the Long-Term Ecological Research program by the National Science Foundation (NSF) of the United States, as a means of coordinating synthesis between LTER sites. Fully

[1]http://goosocean.org/

[2]http://www.goosocean.org/eov

[3]https://www.ilter.network/

supported by the NSF until 2003, ILTER gradually became a self-reliant network, growing from three founding members to 34 organizations by 2006, when a 10-year strategic plan was ratified (ILTER, 2006). At that time, ILTER transitioned to a broader disciplinary approach that included researchers, managers and stakeholders (ILTER, 2006). In 2007, the ILTER Association was founded in Costa Rica, making the ILTER a legal entity with its own governance structure, unifying strategy, operational goals and by-laws (Mirtl et al., 2018). Formally, member networks join the ILTER Association.

The ILTER Network provides a globally distributed network of long-term research sites for multiple purposes and uses in the fields of ecosystem, biodiversity, critical zone, and socio-ecological research (Mirtl et al., 2018). It currently consists of 44 national networks with robust governance structures, managing more than 700 sites worldwide, with a systematic coverage of terrestrial, freshwater, and marine environments (Haase et al., 2018; Mirtl et al., 2018). This site-based research network measures a broad variety of abiotic and biotic environmental variables, which may feed into other global initiatives. LTER national networks have mainly been developed from the bottom–up and LTER sites were established for different research and monitoring purposes. The ILTER community has produced tools to harmonize and compare measurements and methods, allowing for data integration workflows and analyses between and within individual LTER sites, to ensure the highest quality interoperable services in close interaction with related regional and global research infrastructures and networks (Haase et al., 2018; Mirtl et al., 2018). Long Term Socio-economic and Ecosystem Research (LTSER) platforms emerged as initiatives aimed at enhancing the capacity of ecological knowledge combined with social science to produce useful knowledge for facing global environmental challenges (Mauz et al., 2012). This emphasis in the ILTER network reflects the desire to produce knowledge particularly useful for addressing complex environmental challenges emerging from nature-society interactions (Dick et al., 2018).

One of the goals of ILTER is to improve the comparability of site metadata and of long-term ecological data, facilitating their exchange and preservation around the world. ILTER member networks are committed to free and open data sharing (Vanderbilt et al., 2010; Vanderbilt and Gaiser, 2017), in agreement with the F.A.I.R (Findable, Accessible, Interoperable, and Reusable) principles for data management and Open Science (European Commission, 2016 'FAIR'; Mirtl et al., 2018; Tanhua et al., 2019). The Dynamic Ecological Information Management System Site and Dataset Registry (DEIMS-SDR[4]) provides a common and standardized metadata catalog for the distinct identification of observation facilities (e.g., sites, stations, sensors, datasets, persons) used by ILTER members. DEIMS-SDR also provides a web-based service to document and share scientific datasets, implements the ILTER community profile (Kliment and Oggioni, 2011), and allows the export to different XML formats (e.g., EML 2.1.1, BDP, ISO19115, INSPIRE). ILTER identified DataONE as the main facility to share and distribute ILTER data, but it also shares data through the GEOSS (Group on Earth Observation System of Systems[5]) Data Portal. ILTER agrees with the open data principles at the global scale in principle, but putting them into practice is still a challenging issue in most member networks and at the site level.

THE COASTAL AND MARINE ILTER SITES (ILTER-CMS)

There are 63 coastal and 52 marine sites in the ILTER (**Figure 1** and **Supplementary Table S1**). Based on classifications in the ILTER's DEIMS-SDR, coastal sites include sand dunes and beaches, lagoons, estuaries, river deltas, fjords, salt marshes and mangroves, while marine sites are located on continental shelves and oceanic islands (**Figure 2**). Nearly half of the CMS include data records that precede the formal establishment of the ILTER (**Figure 3**). For example, the "Dutch Wadden Sea Area" in the Netherlands has records dating to 1872. Observations began in the Western Gulf of Finland in 1902; the Mar Piccolo of Taranto, Italy in 1914; and Shirahama, Japan in 1922. The length of these observations enhances the opportunities for ILTER-CMS to contribute to documenting global change.

The ILTER-CMS are distributed from tropical-equatorial to polar regions in what can be considered a global observing system (**Figure 1**). There is a large concentration of sites in LTER-Europe, with broad distribution along most of the European Seas. The European LTER sites are predominantly characterized by coastal and transitional waters, such as lagoons, river deltas, estuaries, and fjords. In the Atlantic, sites are located predominantly along the United States, Caribbean, and Brazilian coasts. There is a lack of coverage for the equatorial Atlantic and the African coast, where site distribution is restricted to South Africa. The Indian Ocean has only one oceanic site located at Reunion Island. There are some sites in the South and East China Sea and a good concentration of sites around Japan. In the South Pacific, a coastal site is located in Australia and one oceanic site in Tahiti. In the East Pacific, there are no sites along South America, but only along the Mexican and North American coasts.

The main focus of the ILTER-CMS is on the primary role of ecosystem structure, function, and services in response to a wide range of environmental forcing factors, using long-term, site-based research. Consistent with the general ILTER mission, the coastal and marine sites have been established to contribute to a global, multi-disciplinary community of ecosystem observation and research capable of delivering socially relevant information on sustainable use of natural resources. To that end, ILTER-CMS represents a strong component in a global ocean observation system linking ILTER more strongly into the GOOS framework (**Figure 4**). ILTER-CMS and GOOS can mutually benefit from setting similar requirements and deciding on what to measure, monitor Essential Ocean Variables, and interact through the instrumentation deployment and

[4]http://data.lter-europe.net/deims/

[5]http://www.geoportal.org/

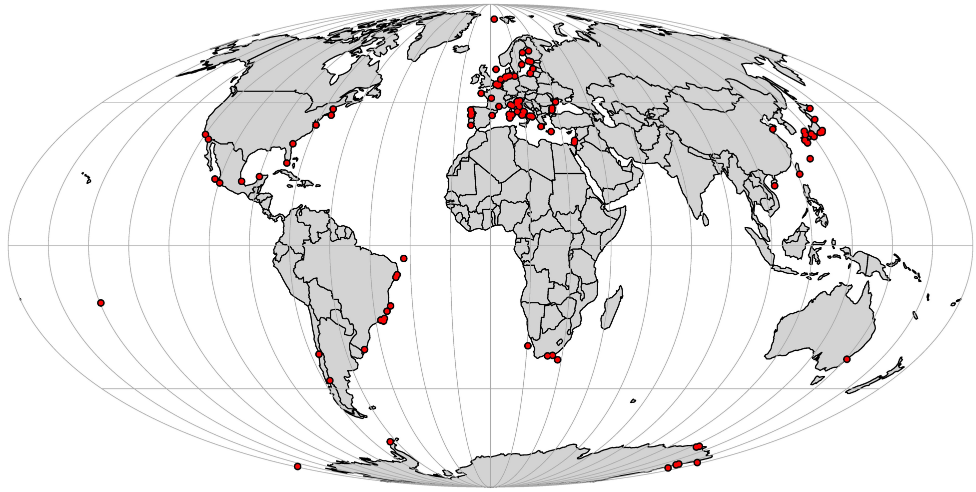

FIGURE 1 | Worldwide distribution of coastal and marine International Long-Term Ecological Research (ILTER) sites. Based on DEIMS status as of 2nd September 2019.

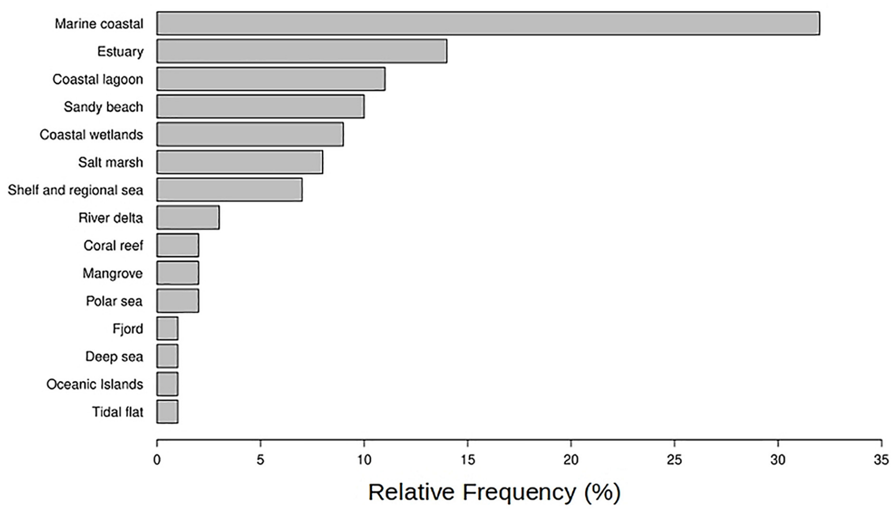

FIGURE 2 | The diversity of habitats represented at coastal and marine International Long-Term Ecological Research sites.

maintenance. ILTER-CMS monitors many biological variables by classical methods, providing added value to the sensor-based measurements in the GOOS program. The LTSER with social science competence can contribute to define issues and priorities and assess the impact of observations on society (**Figure 4**). In the following paragraphs we will briefly analyze the potential for ILTER-CMS to contribute to global coastal and marine observations by means of a "Strengths, Weaknesses, Opportunities and Threats" (SWOT) approach (**Table 1**).

Strengths

- ILTER coastal and marine sites are uniquely poised to contribute to biological and ecosystem EOVs by virtue of the existing ILTER governance, infrastructure, and research resources (both human and technological).
- The long time span of many ILTER-CMS members enables the identification of global trends (e.g., warming) and local pressures (e.g., nutrient loads) against the background of natural variation. Recent evidence of global changes and impacts from marine organisms and ecosystems are mainly derived from global databases of *in situ* observations (Poloczanska et al., 2016), stressing the value of global networks such as ILTER-CMS.
- A marked diversity and wide range of partners and institutions across the globe characterize ILTER-CMS, guaranteeing multi-disciplinary data acquisition, analysis, integration and synthesis, and cost-effective sustainable observations.

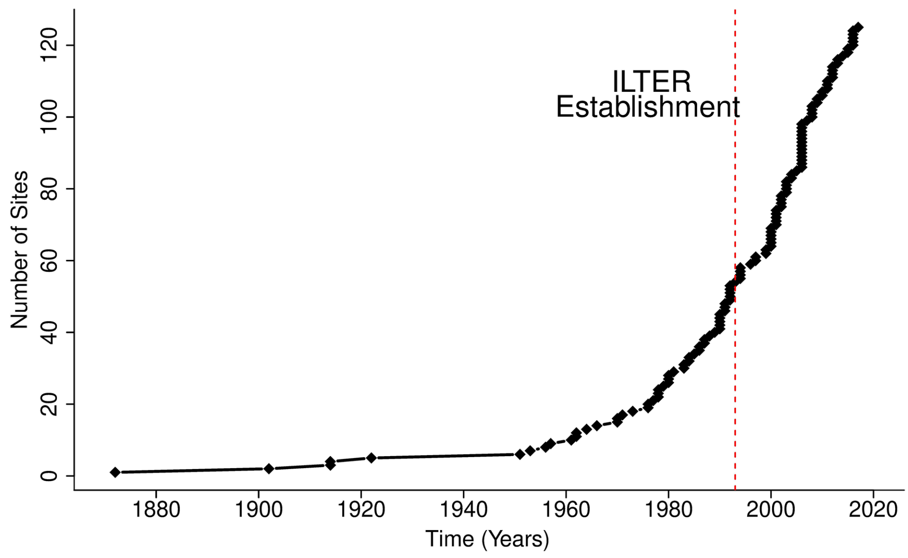

FIGURE 3 | Timeline of the establishment of long-term coastal and marine observation sites and the implementation of the International Long-Term Ecological Research (ILTER) Program.

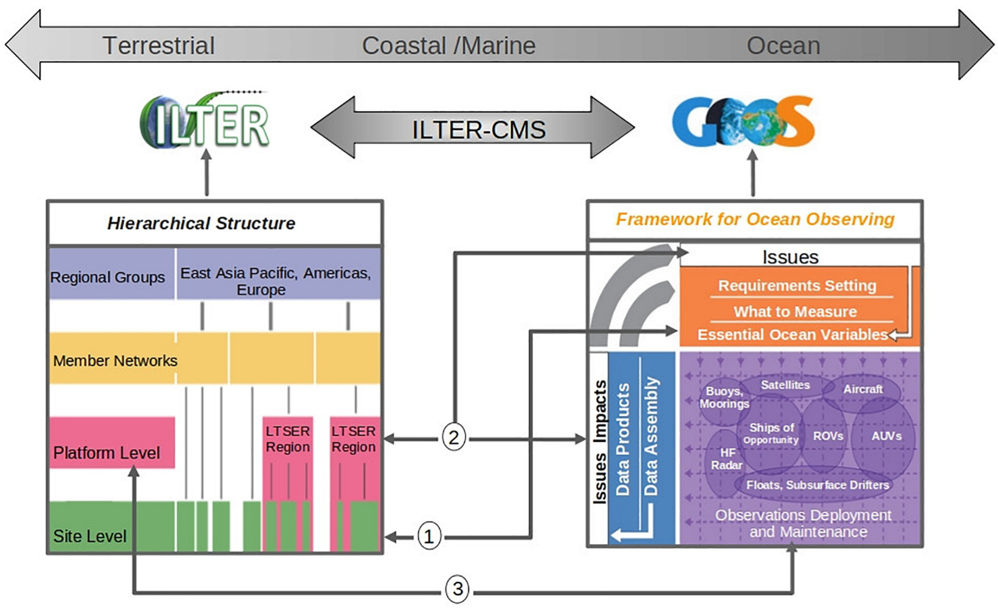

FIGURE 4 | ILTER coastal and marine sites can provide several interaction points between the ILTER structure and the GOOS Framework. ILTER-CMS and GOOS can mutually benefit from setting similar requirements and deciding on what to measure. (1) ILTER sites can provide GOOS with monitoring of Essential Ocean Variables, including many biological variables by classical methods, providing added value to the sensor–based measurements in the GOOS program. (2) The LTSER with social science competence can contribute to define issues and priorities and assess the impact of observations on society. (3) At the platform level the interaction can take place through instrumentation deployment and maintenance.

- The ILTER Network provides a platform for discussion among experts and stakeholders on key oceanographic and ecological themes, optimizing active links or developing new ones with a diverse array of global and regional processes and initiatives. Indeed, since its onset, ILTER had adopted a more interdisciplinary approach to research and monitoring, recognizing that in dealing with environmental problems, natural and human systems cannot be considered as separate entities (Dick et al., 2018). ILTER-CMS provides and fosters the use of standard protocols and open access data. This is critical for the study of climate change

TABLE 1 | The strengths, weakness, opportunities, and threats presented by the ILTER-CMS.

Strengths	Weakness
• Multi- and interdisciplinary • Links with a wide range of global/regional processes and initiatives • Platform for discussion among experts on oceanographical and ecological themes • Multi-institutional cooperation • Metadata organized and updated in DEIMS-SDR • Socio-ecological aspects developed in the ILTER mission • ILTER-CMS monitor Physical, Biochemical, and Biological/Ecological EOVs • Potential for large syntheses and detection of long-term trends across sites, spatial and temporal scales • Potential for developing and testing concepts and theoretical frameworks • A consolidated data policy and information availability system • Quick response to methodological/technological advances, standardization and implementation of these technologies on a large spatial scale and link to existing time series and spatial data	• ILTER is mostly terrestrial, overarching strategy and conceptual framework are broad and not specific for coastal and marine environments. • Variables to be measured, methodologies, technological development and sampling schemes are not homogeneous among sites • The socio-ecological aspects are not yet fully developed • Harmonization of data and metadata for coastal and marine environments is still incomplete • The geographic location of time series has notable gaps • The standardization of variables gathered has not been accomplished, and EEVs or EOVs coverage is inconsistent • Intercalibration of approaches and methodologies is lacking • The data management is relatively poor at several sites • Some data linked to ecological research activities not immediately available
Opportunities	**Threats**
• Optimal sites for experiments on observation and pilot integrated biological observatories • Promote the use of new technologies for ocean observation and compare the information that technologies make available • Merging frameworks from different global research and monitoring initiatives, producing guidelines for future site-based long-term research and monitoring marine and coastal ecosystems • Support the use of costly infrastructure, fostering cross-initiative collaborative research • Monitoring EOVs at a global scale at 115 discrete sites • Improvement of models and predictions of possible future developments • Platform for citizen science • Continuous training of new generations of scientists, ensuring the transfer of knowledge	• Missing link with society, hampering the identification of questions with societal relevance • Reduction in focus on *in-situ* sampling as a consequence of linking with more technological or model-centric networks • Inadequate training of new generation of researchers with relevant skills set (e.g., taxonomy, data science, database management), able to recognize the relevance of these kinds of activities and maintain LTER in the future • Reduction of ILTER activities at some sites leading to temporal and spatial gaps.

and its effect on biota and ecosystems. Additionally, ILTER-CMS already monitors Physical, Biochemical, and Biological/Ecological EOVs.

Weaknesses

- Most LTER sites and national networks have been developed from the bottom–up. The different research and monitoring aims, some of which may have changed over time, as well as the wide variety of ecosystem types, infrastructure, instrumentation and technological development may all hinder comparisons within and across networks, sites and scales.
- ILTER-CMS is a relatively new network, with 50% of the sites being established after the year 2000. Environmental and socio-ecological issues are often regional and not yet clearly defined at the global scale.
- Despite recent efforts (Haase et al., 2018) and progress with the development of the DEIMS-SDR, the harmonization of data and metadata for CMS is still far from complete. Standardized/transparent data management procedures cannot easily be implemented in a number of locations and datasets are often not readily available. The obstacles include inadequate funding, a lack of training opportunities, and/or hesitancy to submit data to internationally accepted repositories.
- ILTER-CMS was not designed to be an operational monitoring system but to study ecosystem and biodiversity. Consequently, there is not final consensus about the variables to be measured and the methodologies and sampling schemes that should be adopted.

Opportunities

- ILTER-CMS has the governance structure to coordinate with management and policy programs, interact and link with other large-scale initiatives, create interfaces between the different approaches from the various communities, and establish a co-located network of sites within similar ecosystem typologies, with shared research and monitoring tasks for multi-purpose uses (Haase et al., 2018). The ILTER-CMS can contribute substantially to merging frameworks that are behind different global research and monitoring initiatives, producing guidelines for future site-based long-term research and monitoring. The site network could generate connected ecosystem monitoring methodologies and datasets, supporting, as well, synergies in the use of costly infrastructures, through cross-initiative collaborative research.
- Stakeholder interactions play a key role in implementing ILTER outcomes for sustainable regional and local development in light of global trends, and for true integration of the sites into local/regional innovation systems, where the societal and human dimension is considered together with the scientific one. Long-term ecosystem studies, in comparison to the public funding they need, possess a disproportionately high capacity to inform policymakers about relevant environmental issues (Hughes et al., 2017). The ILTER-CMS represent ideal places for establishing pilot

integrated biological observatories where the use of new technologies for ocean observation can also be promoted and where the information that technologies make available can be tested and compared to develop standardized approaches for their use (e.g., high throughput molecular or imaging techniques). With enhanced standardization and increased adoption across coastal and marine sites, the ILTER offers the opportunity to monitor EOVs at a global scale.

- The interaction between modelers and observers provides the opportunity to better design and plan new long-term observation initiatives. Several sites record periods of decades and thus a large number of different past conditions, which can be used to calibrate and validate various kinds of models. Model-generated environmental parameters can help to reduce temporal and spatial observation gaps. Advanced models are vital to create reliable (future) scenarios that facilitate the understanding of ecosystem functioning and evolution and are necessary to improve links between science and policy makers. Observations can be used to generate operational models needed to sustainably manage and protect marine and coastal ecosystems (ODS 14.2) by indicating areas of adverse impacts, habitat loss, and changes in ocean state that are relevant for ecosystems services. ILTER can strengthen capacity building by providing site access and training on advanced ecosystem monitoring and management. This is an invaluable opportunity to attract young scientists from around the globe and to teach a new generation of scientists innovative ways to use resources, recognize the relevance of these kinds of activities, and maintain and develop the network with a long-term perspective.
- ILTER-CMS could be an ideal context for the development of citizen science (CS) activities (Irwin, 1995; Bonney et al., 2009). CS can (i) improve the frequency and geographical coverage of observations, and (ii) improve pedagogy and communication at the science/society/policy interface by involving citizens, managers or different stakeholders in a research program. Hands-on involvement of people in research and monitoring activities is more effective than communicating about science and its benefits. Increasingly apps can be used to assist the citizen scientists to report data in a standardized manner (e.g., the Secchi disk project[6] or beach observer). CS programs can yield significant results (see, e.g., Abbott et al., 2018) and could be applied, for example, in programs with divers, sailors, and beach-goers looking at biodiversity in coastal zones and collecting data of great interest to ILTER and contributing to GOOS.
- ILTER Network may provide improved data management at site-level and enhanced data flow toward global and European marine data infrastructure like the Ocean Biogeographic Information System (OBIS) and the European Marine Observation and Data Network (EMODnet). ILTER may make use as well of the standardization tools provided by World Register of Marine Species (WoRMS) and the improved analytical capacity provided by marine virtual research environments constructed under the European Research Infrastructure (ESFRI) by LifeWatch-ERIC and the European Open Science Cloud.
- The concepts of EOVs and Essential Biodiversity variables (EBVs) could facilitate the task of identifying key variables for LTER coastal and marine biological observations (Miloslavich et al., 2018; Navarro et al., 2018). ILTER-CMS needs to assess the readiness levels of the EOVs to assure implementation of an operational system. These concepts could be merged with the Ecosystem Integrity framework (Müller, 2005), at the moment adopted by ILTER, based on a comprehensive set of abiotic variables for identifying drivers of biodiversity changes within the context of ecosystem structures and processes (Haase et al., 2018).

Threats

- Long-term initiatives are difficult to maintain, and they need to be cost-effective and sustainable at the country level. Reduction of ILTER-CMS activities at some sites could produce temporal and spatial gaps that would hamper the functionality and relevance of the network.
- A failure in engaging users and stakeholders could limit the full exploitation of ILTER-CMS services and products. The lack of transfer of knowledge and understanding to policy makers and society would prevent informed decision making regarding the long-term safeguarding and effective management of marine ecosystem services.
- ILTER Network has historically been more oriented toward "terrestrial," inland ecosystems: conceptual frameworks, harmonization, and data models not well-suited for the marine component may discourage future ocean initiatives.
- Future ILTER-CMS activities must be sustained by young scientists. A failure to make ILTER-CMS attractive and meaningful for early career researchers (and the next generation of stakeholders) could be a major threat for the long-term sustainability of integrated coastal and marine ecological observatories.

In the following two sections, we elaborate on two specific opportunities for ILTER-CMS in contributing to global ocean observing: Essential Ocean Variables and Emerging Technology.

Essential Ocean Variables and the ILTER Contribution to Observation, Science and Management Programs

Many programs and initiatives at the regional and global level are dedicated to the study of coastal and marine environments and they express a common need to harmonize and coordinate observations to allow comparison and synthesis across ecosystems and scales. In this respect, efforts need to be dedicated to enable interoperability and to create interfaces among the different initiatives. In particular, consolidated global networks, such as GOOS and ILTER, should be leaders in proposing and demonstrating how interoperability and linking of conceptual frameworks could be tackled.

We argue that one way to achieve this integration is through the use of Essential Ecosystem Variables (EEVs) or EOVs.

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

One of the outputs of the OceanObs'09 conference was the adoption of FOO (Lindstrom et al., 2012). The FOO proposed the use of routine and sustained observations of physical, biogeochemical and biological EOVs. GOOS has adopted the FOO recommendations, and recently the Biology and Ecosystem Panel has approved a set of EOVs for global sustained observations of biodiversity and ecosystem change (Miloslavich et al., 2018). This is also in line with a recent joint proposition of ILTER and the Group on Earth Observations Biodiversity Observation Network (GEOBON) to merge ecosystem integrity and EBVs to serve as an improved guideline for future long-term environmental research and monitoring (Haase et al., 2018).

As a first step, we conducted a survey involving ILTER-CMS site managers in order to record how many sites already monitor the EOVs proposed by the GOOS. The GOOS Panels have identified 11 Physical, 9 Biogeochemical, and 11 Biological/Ecosystem essential variables. The results of the survey were quite encouraging (**Figure 5**). Eleven EOVs are observed routinely in more than 50% of the surveyed sites. Surface and sub-surface temperature and salinity are among the most observed physical EOVs, but a good number of sites also measure sea state (42%), surface (42%) and sub-surface currents (42%) and sea surface height (38%). The most common physical EOVs within ILTER-CMS sites (**Figure 5**) are already in a mature readiness level. For the biogeochemical EOVs, nutrients, oxygen and particulate matter are measured in more than 50% of the sites, while inorganic carbon (40%), dissolved organic carbon (40%) and ocean color (32%) are also well-represented. Nutrients and oxygen are at a mature level while particular matter can vary from concept to mature depending on the environment. Phytoplankton biomass and diversity, the abundance and distribution of benthic invertebrates, fish and zooplankton are the biological/ecosystem EOVs measured at 50% or more sites. These EOVs have a varying degree of readiness level, ranging from concept to mature. Other biological/ecosystem EOVs are site specific and reflect habitat specificity. Therefore, it is expected that seagrass, hard coral, and mangrove covers would only be measured at a few sites.

ILTER coastal and marine sites also measure several other variables that are relevant for coastal and marine ecosystems, but are not indicated as EOVs. Among them: physical (e.g., incident wave height and cumulative wave energy, and currents along the entire water column parameters), water quality (e.g., transparency, turbidity, sediment concentration, and composition) and biogeochemical and biological parameters (redox potential and water pH, CO_2 fluxes to and from the atmosphere, primary productivity, toxic phytoplankton composition, and production of toxins).

These results show that a comprehensive coastal and marine ecosystem monitoring system could benefit from collaboration and synergy with the ILTER network. At this time, when GOOS has just defined biological/ecological EOVs and is working on implementation strategies and coordination of observations, the ILTER network already provides infrastructure and logistical support to conduct monitoring of coastal and marine ecosystems around the world.

Another possible contribution of the ILTER-CMS observations is the establishment of integrated supersites. Supersites are focal points for instrument intensive research, ideally suited for co-location with small-scale experiments and specialized observations, and situated in areas that will provide important information on environmental change, i.e., critical zones. Co-locating ILTER-CMS supersites with GOOS-proposed Sentinel sites (PICO-I, 2012) would link the mechanistic ecological and biophysical understanding from the ILTER with an ocean observatory framework that explicitly seeks to understand the influence of anthropogenic pressures and the roles of ecosystem services in that location. ILTER has sites in most Sentinel Sites including some of the most stressed ones: Greenland-North-Baltic Seas/Bay of Biscay; Indonesian Archipelago-South China Sea; and, East China/Yellow Seas. Thus, the ILTER-CMS is poised to provide observations of scientific and societal benefit immediately to vulnerable regions.

Long-term ecological time series are crucial for setting realistic baselines and limits in the classification systems used for assessing ecosystem environmental status. The 115 globally-distributed coastal and marine sites of the ILTER provide an exceptional observation platform for the GOOS-defined EOVs and invaluable information for several regional and global programs. This integration could benefit the European Water Framework Directive (WFD) and the EU Marine Strategy Framework Directive (MSFD), the accomplishment of the Aichi Targets of the Convention for Biological Diversity (CBD), the Intergovernmental Panel for Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the United Nations World Ocean Assessment. Information on coastal and marine ecosystems is urgently required to address the UN Sustainable Development Goal (SDG) 14.

ILTER coastal and marine sites can also provide information for science programs such as Future Earth Coasts, formerly LOICZ (Land-Ocean Interactions in the Coastal Zone) programme. Future Earth Coasts was launched by IGBP (International Geosphere-Biosphere Programme) and IHDP (International Human Dimensions Programme) as an international research project and global expert network exploring the pressures and social-environmental impacts of global environmental change in coastal zones. ILTER-CMS can also contribute to the Marine Biodiversity Observation Network (MBON), a thematic component of GEO BON, that aims to coordinate, promote and augment the capabilities of present and future national and international observing systems to characterize and monitor diversity of marine life at the genetic, species, and ecosystem levels using a broad array of *in situ* and remote sensing observations (Duffy et al., 2013; Muller-Karger et al., 2018). ILTER-CMS sites are located in 20 of the 66 Large Marine Ecosystem (LME, Sherman, 1991) around the world and can contribute to identify areas of the oceans for conservation purposes and enable ecosystem-based management to provide a collaborative approach to management of resources within ecologically-bounded transnational areas. Data collected at ILTER-CMS

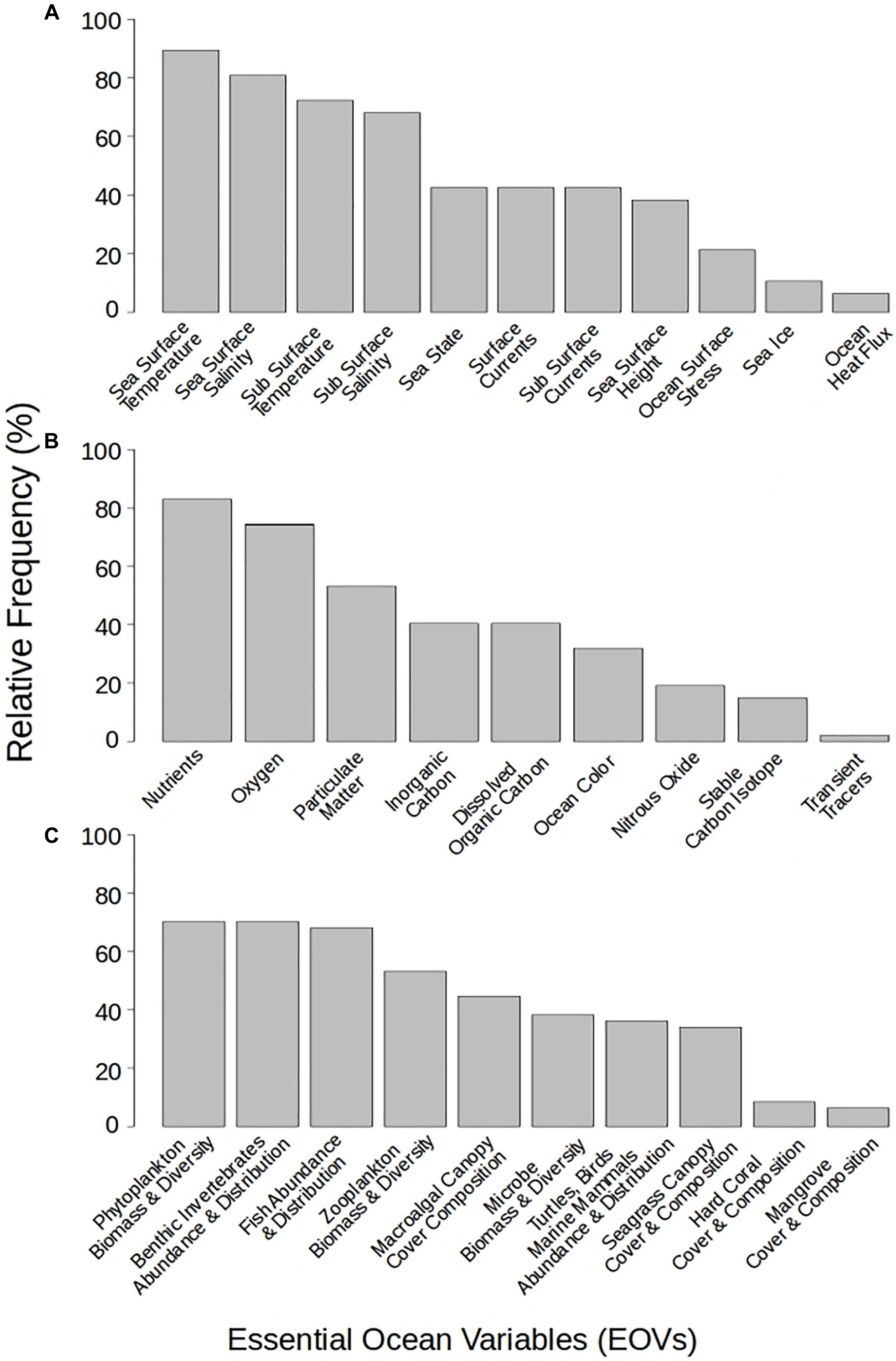

FIGURE 5 | Frequency of coastal and marine International Long-Term Ecological Research (ILTER) sites that observe Essential Ocean Variables recommended by the GOOS Biology and Ecosystem Panel. Physical variables **(A)**, biogeochemical variables **(B)**, and biological/ecosystem variables **(C)**.

could be streamed into the OBIS and contribute to increasingly free and open access biodiversity and biogeographic data and information on marine life. ILTER can harbor and link with many other long-term coastal and ocean ecosystem monitoring programs, which may be explicitly reported also on DEIMS – SDR, in each site description. Furthermore, there is a well-established bottom–up procedure from the request of a site to become an LTER site, to the assessment of its suitability, i.e., of the possession of specific requisites fulfilling the LTER network requirements, which occurs at the national level, to the admittance to the national network and hence to ILTER.

NEW TECHNOLOGIES FOR ILTER

One aspect determining the future success of the ILTER will be its ability to adopt and leverage emerging technologies at all levels of organization. Many of these technological developments represent opportunities to catalyze education of and collaboration between young scientists across LTER sites, strengthening the network and thus mitigate identified threats in the SWOT-analysis (**Table 1**). Mature technologies that are economic to implement can directly contribute to counteract currently identified weaknesses by better geographical coverage and harmonized data quality. This spans innovative *in situ* technologies developed at individual sites to global data networks that enable novel syntheses via increasingly powerful computational technologies or leverage citizen science. Here we consider some of these technologies, building up through the hierarchical organization of ILTER (see **Figure 4** in Mirtl et al., 2018).

Researcher Level

International Long-Term Ecological Research Network sites are ideal incubators for the development and/or deployment of emerging technologies. As noted in the introduction, the general sampling rate of eco/bio/geo/chemical phenomena has long lagged behind the rapid data collection possible by physical oceanographers. In the last two decades, however, there has been a rapid development of novel high-throughput technologies. These include chemical, imaging, acoustic and molecular sensor systems that have enabled continuous and long-term measurement of new parameters that are of great interest (Johnson et al., 2007). Examples include nitrate (Johnson and Coletti, 2002), ammonium (Plant et al., 2009), and pH (Seidel et al., 2008; Martz et al., 2010) sensors. Similarly, advances in rapid image collection and processing have enabled cataloging and enumeration of phytoplankton and zooplankton biodiversity at tidal to interannual scales (Olson and Sosik, 2007; Sosik and Olson, 2007; Faillettaz et al., 2016; Hunter-Cevera et al., 2016), while high-throughput molecular analyses facilitate biodiversity assessments of unprecedented taxonomic resolution, facilitating the regular monitoring of taxa that were not reliably identifiable previously (Stern et al., 2018). This, in turn, provides the potential for unique insights into the diversity and function of marine foodwebs (e.g., Leray et al., 2015).

One major trend that will shape the future of ILTER research is the continued miniaturization of electronics and improvements to memory and batteries. For example, the Imaging FlowCytobot is now half as large, weighs half as much, and consumes one-third of the power of the original (Olson et al., 2017). This technology has now been commercialized (McLane Research Laboratories, Inc.), is in routine use at the Northeast U.S. Shelf (NES) LTER site and other time series locations in the U.S., and has a growing user base around the world. Continued advances along this trajectory will enable novel biological and ecological studies. For example, embedded sensors within organisms have enabled metabolic and physiological studies (McGaw et al., 2018); underwater tracking technology has revealed ecological interactions between predator, prey and the environment (Osterback et al., 2013). The rich contextual data at the ILTER sites provide an ideal framework to develop this new technology and interpret the data it produces.

In addition to developments of *in situ* technologies, ILTER sites are also promoting advances in remote sensing technologies that are critical for characterizing ecosystems at large scales. For example, in coastal dune systems the use of high-resolution remote sensed imagery (LiDAR – Light Detection and Ranging – and orthophotos) is helping to explain the invasion success of some alien species and the roles of propagule pressure, abiotic, and biotic factors in coastal landscapes (Bazzichetto et al., 2018). The use of remotely sensed data may make it possible to model the invader-landscape relationship over a large geographic extent and to highlight the coastal sectors that are most likely to be invaded in the future.

Site Level

Across individual ILTER sites (which may comprise a number of individual locations), autonomous systems, robotics, machine learning, and advances in -omics technologies will drive discovery in the coming decades.

The maturation and miniaturization of robotic platforms (taken here to be all manner of autonomous mobile platforms, including drifters, profiling floats, buoyancy gliders, propeller-driven autonomous underwater vehicles, and unmanned aerial systems, cf. Nidzieko et al., 2018) will gradually enable their incorporation into a broader range of research. There are three barriers to more widespread adoption at the moment. One, the maturation of suitable sensors, as mentioned above, is necessary prior to incorporation onto mobile platforms. Two, most platforms are still not "turnkey" devices and thus require specialized operator knowledge. And three, costs are still prohibitive for acquisition of more mature technologies. The popular trend of the DIY/makerspace ethos may result in less costly, yet still capable platforms that can be readily employed in coastal and marine research. Once deployed, however, the ability of robots to do "dull, dirty, dangerous" tasks will improve both the temporal and spatial measurements collected across an LTER site. For example, the time-consuming task of manually counting kelp forest biomass is only conducted monthly across all 10 of the individual sites within the Santa Barbara Coastal LTER and measurements are done on subsampled transects within a kelp forest. Underwater and/or aerial platforms could be used to survey the entire 70 km coastline on a weekly basis, enabling better understanding spatial patterns in synchrony and disturbance (Bell et al., 2015).

Machine learning will enable the deployment of technologies that have heretofore been too data-rich to make significant impacts to understanding biology and ecology within LTER sites. We give two examples: passive acoustics and flow cytometers. The use of passive acoustics across a broad sound spectrum has not been feasible due to limitations in memory, battery power, and processing capabilities. With the advances mentioned above and the maturation of machine learning techniques in parallel with increasingly powerful computers (at both the personal and cloud/cluster level), tackling the processing requirements of such large datasets in now feasible (Mooney et al., 2017). We envision that monitoring the soundscape within ILTER-CMS will become one of the most widely adopted technologies in the coming decade. Flow cytometry techniques similarly produce massive amounts of data and have traditionally required extensive manual efforts to classify cytometric and image data into quantified products; the potential for automation of these tasks across ILTER sites could revolutionize researcher's understanding of variations in plankton biodiversity.

Finally, at the site level, emerging molecular methods will bring major insights by identifying important microbial actors, determining their interactions, and providing deeper insights into biogeochemical processes at ILTER sites. One example of this technology is the MBARI Environmental Sample Processor (Scholin et al., 2009), which has been used to autonomously collect and preserve microbial samples (Ottesen et al., 2011), revealing complex shifts in microbial communities over very short time scales (Needham et al., 2018). See McQuillan and Robidart (2017) for a comprehensive review of recent advances. Importantly, these technological advances are multiplicative: not only are the measurement techniques novel and advanced, but these measurements can also be conducted adaptively in response to the feature or event of interest (Harvey et al., 2012). Furthermore, these technologies can present advantages in accuracy, efficiency, and cost (Danovaro et al., 2016). It is important though that all new observing technologies pass through the four stages of evolution of a sustained Ocean Observing system (Nowlin et al., 2001).

Regional/Global Levels

While many of the roles of technology at the researcher and site levels will provide fundamental disciplinary discoveries and enable the establishment of new time series for incorporation into ILTER core products, several aspects of technology will drive the interdisciplinary discoveries that integrate multiple sites at regional and/or global levels. First, common metadata and easy, rapid access to data assets are essential to synthesis efforts. Improvements to cloud storage and data discovery tools will be critical to this end (Buck et al., 2019). As these tools mature, and perhaps converge from bespoke applications into more generic platforms, ILTER data will become an integral component of the broader suite of data products provided from regional observing systems, operational (and data assimilative) forecasts, numerical hindcasts, and weather data that researchers draw upon.

The major challenge to delivering the sound ecological knowledge necessary to address human impacts will require incorporating patterns/trends from site-level records into observed and predicted global climate models. This is not a trivial task, because it requires both scaling up local measurements to discover and explain emergent patterns (that might only be detectable within the distributed network of the ILTER) while also scaling down from climate predictions to expectations/hypotheses of what might be observed at individual site. Synthesis using cross ILTER site have contributed to the knowledge of ecosystem spatial and temporal variability (e.g., Bestelmeyer et al., 2011), and serve as example that this challenge can be addressed. Advances in computational capabilities will certainly be an asset to this end, but ultimately the larger hurdle may be not be technological be rather operational, as described in the threats above.

RECOMMENDATIONS AND CHALLENGES

ILTER coastal and marine sites has great potential to contribute to global coastal and ocean observation. Here we provide recommendations to improve the opportunities for ILTER-CMS to enhance collaboration among researchers, institutions and governments and funding agencies in support of long-term ocean observing initiatives.

(1) Recommendations to the network members and related organizations:

- Regional nodes should promote the expansion of coastal and marine sites by strengthening networks of marine scientists.
- Financial and educational support necessary to minimize the coverage gaps of ILTER-CMS (**Figure 1**), especially in developing countries should be addressed.
- Members should provide a quality-assured web-based data archiving, effective data retrieval and relevant data products within the network; promote the use of best-available statistical tools for data analysis and synthesis; and build up their respective infrastructures for sharing data and data handling, analysis and visualization.
- The ILTER-CMS need to harmonize and coordinate long-term environmental (both biotic and abiotic) observations in line with the EOVs to the extent possible, to allow comparisons within and across networks, sites and scales. These efforts should consider socio-ecological aspects, as well.
- Launch or improve coordination and integration of observations across scales (e.g., from coast to open sea) in concert with other international observing networks.
- Develop standard operating procedures, adopt guidelines for measurement program design, and establish routines for recurrent intercalibration exercises for all subject fields in line with the OceanBestPractices (OBP[7]). Such activities may include increasing the use of shared infrastructure, protocols and data platforms; and developing metadata and dataset harmonization/interoperability necessary to foster and facilitate sharing and open access.
- Define a consistent overarching research and monitoring framework, taking into account the wide range of ILTER-CMS typologies. LTER has historically been more oriented toward terrestrial, inland ecosystems, therefore coastal and marine conceptual frameworks, harmonization and data models still need improvement and should be strengthened and better integrated.

[7] https://www.oceanbestpractices.net/

- Strengthen the communication with relevant stakeholders to improve the role of ILTER-CMS network as a data and knowledge provider for society.
- Promote citizen science initiatives to raise awareness about the broad importance of ILTER-CMS research activities. A collaboration with existing citizen science networks, e.g., ECSA (European Citizen Science Association) and other observation networks should be encouraged.
- Seek consensus for the adoption of parameters and monitoring methods in order to overcome fragmentation between sites, improve interfaces among networks (e.g., GOOS) and promote cooperation on shared environmental issues and targets.
- Further develop existing biological observations through the implementation of new technological and -omic approaches and improve their integration with physical and chemical observing systems and modeling initiatives.
- Provide the knowledge needed by policy makers and society for informed decision-making regarding the long-term safeguarding and effective management and sustainability of coastal and marine ecosystem services.

(2) General recommendations to government, funding agencies, and other organizations:

- Partners should address the need to support and protect existing LTER sites, recruit technical workforce, allow for their development and improvement, and increase their number for better spatial coverage, while recognizing funding limitations.
- Support formation of expert working groups providing urgent scientific environmental knowledge for society, capacity strengthening, education, and training.
- Support technological innovation to implement *in situ* observing systems, develop smart technologies for cost-effective automated monitoring of biological variables, and transition from research to operational status.
- Engage society in the definition of relevant research questions to strengthen the science/society/policy interface.
- Engage governments in prioritizing and sustaining ILTER-CMS activities as well as engage users, stakeholders, and other existing observing networks to fully exploit ILTER services and products, and demonstrate the impact on science and society.

AUTHOR CONTRIBUTIONS

JM, NN, AA, AB, AK, AP, and AZ helped to conceive the manuscript, coordinated the author contributions, wrote and edited the manuscript, and contributed to tables and figures. SB, EB, TB, BC, KD, EE, MN, OR, MS, TS, HS, AdS, KS, PS, AnS, and JW contributed to manuscript ideas and text.

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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.2019.00527/full#supplementary-material

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Corrigendum: ILTER – The International Long-Term Ecological Research Network as a Platform for Global Coastal and Ocean Observation

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A Corrigendum on

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In the original article, there was a mistake in the legend for **Figure 1** as published. After publication, it was brought to the authors' attention that DEIMS-SDR also included not-LTER sites (Wohner et al., 2019) and the so called LTER "parent sites," at the same hierarchical level of the research sites they are made of, generating some duplicates. While reviewing the site list, it was found that one site was duplicated and seven LTER sites were not included. Therefore, the published map included seven not-ILTER sites, 10 parent sites, and one duplicated site, all of which have now been removed. The correct legend appears below.

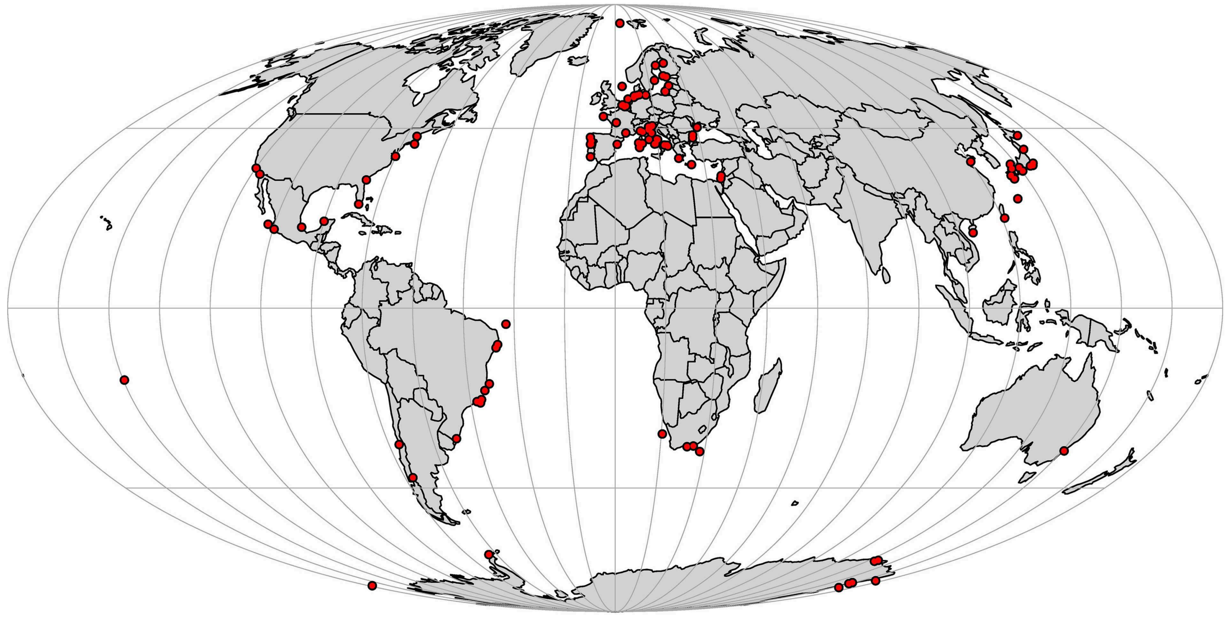

Figure 1 | Worldwide distribution of coastal and marine International Long-Term Ecological Research (ILTER) sites. Based on DEIMS status as of 2nd September 2019.

TABLE 1 | The strengths, weakness, opportunities and threats presented by the ILTER-CMS.

Strengths	Weakness
• Multi- and interdisciplinary • Links with a wide range of global/regional processes and initiatives • Platform for discussion among experts on oceanographical and ecological themes • Multi-institutional cooperation • Metadata organized and updated in DEIMS-SDR • Socio-ecological aspects developed in the ILTER mission • ILTER-CMS monitor Physical, Biochemical, and Biological/Ecological EOVs • Potential for large syntheses and detection of long-term trends across sites, spatial and temporal scales • Potential for developing and testing concepts and theoretical frameworks • A consolidated data policy and information availability system • Quick response to methodological/technological advances, standardization and implementation of these technologies on a large spatial scale and link to existing time series and spatial data	• ILTER is mostly terrestrial, overarching strategy and conceptual framework are broad and not specific for coastal and marine environments. • Variables to be measured, methodologies, technological development and sampling schemes are not homogeneous among sites • The socio-ecological aspects are not yet fully developed • Harmonization of data and metadata for coastal and marine environments is still incomplete • The geographic location of time series has notable gaps • The standardization of variables gathered has not been accomplished, and EEVs or EOVs coverage is inconsistent • Intercalibration of approaches and methodologies is lacking • The data management is relatively poor at several sites • Some data linked to ecological research activities not immediately available
Opportunities	**Threats**
• Optimal sites for experiments on observation and pilot integrated biological observatories • Promote the use of new technologies for ocean observation and compare the information that technologies make available • Merging frameworks from different global research and monitoring initiatives, producing guidelines for future site-based long-term research and monitoring marine and coastal ecosystems • Support the use of costly infrastructure, fostering cross-initiative collaborative research • Monitoring EOVs at a global scale at 115 discrete sites • Improvement of models and predictions of possible future developments • Platform for citizen science • Continuous training of new generations of scientists, ensuring the transfer of knowledge	• Missing link with society, hampering the identification of questions with societal relevance • Reduction in focus on *in-situ* sampling as a consequence of linking with more technological or model-centric networks • Inadequate training of new generation of researchers with relevant skills set (e.g., taxonomy, data science, database management), able to recognize the relevance of these kinds of activities and maintain LTER in the future • Reduction of ILTER activities at some sites leading to temporal and spatial gaps.

Further, in the original article, there was a mistake in the legend for **Table S1** as published. The table included seven not-ILTER sites, 10 parent sites, one duplicated site and excluded seven LTER sites. The correct legend appears below.

"**Table S1**. ILTER-CMS site name, location, year of establishment and habitat type. Site name, geographic coordinates and establishment obtained from DEIMS (https://deims.org/site/list) on 2nd September 2019. Habitat type was obtained with a survey conducted with ILTER-CMS site managers for this study. Negative longitudes refer to West, negative latitudes to South."

Additionally, there was a mistake in **Figure 1** as published. Locations on the map included the seven not-ILTER sites, 10 parent sites, and one duplicated site and excluded the seven LTER sites. The corrected **Figure 1** appears above.

There was also a mistake in **Table 1** as published. The inclusion of not-LTER and parent sites at the same hierarchical level on DEIMS-SDR, and the repetition of one site lead the authors to list "130" sites in the ILTER-CMS. Added to the seven LTER sites not listed, the correct number of ILTER-CMS sites is "115." The corrected **Table 1** appears above.

The inclusion of not-LTER sites and parent sites on DEIMS-SDR and the duplicated site lead the authors to inform the existence of "70 coastal and 60 marine sites" in the ILTER. After these corrections and the inclusion of the seven missing LTER sites, the correct number is "63 coastal and 52 marine sites" in the ILTER.

A correction has been made to the section The Coastal and Marine ILTER Sites (ILTER-CMS), paragraph one:

"There are 63 coastal and 52 marine sites in the ILTER (**Figure 1** and **Table S1**). Based on classifications in the ILTER's DEIMS-SDR, coastal sites include sand dunes and beaches, lagoons, estuaries, river deltas, fjords, salt marshes and mangroves, while marine sites are located on continental shelves and oceanic islands (Figure 2). Nearly half of the CMS include data records that precede the formal establishment of the ILTER (Figure 3). For example, the "Dutch Wadden Sea Area" in the Netherlands has records dating to 1872. Observations began in the Western Gulf of Finland in 1902; the Mar Piccolo of Taranto, Italy in 1914; and Shirahama, Japan in 1922. The length of these observations enhances the opportunities for ILTER-CMS to contribute to documenting global change."

The inclusion of not-LTER sites on DEIMS-SDR lead the authors to inform the existence of "130" sites in the ILTER, when the correct number of ILTER-CMS sites is "115."

A correction has been made to The Coastal and Marine ILTER Sites (ILTER-CMS), paragraph seven:

"Long-term ecological time series are crucial for setting realistic baselines and limits in the classification systems used for assessing ecosystem environmental status. The 115 globally-distributed coastal and marine sites of the ILTER provide an exceptional observation platform for the GOOS-defined EOVs and invaluable information for several regional and global programs. This integration could benefit the European Water Framework Directive (WFD) and the EU Marine Strategy Framework Directive (MSFD), the accomplishment of the Aichi Targets of the Convention for Biological Diversity (CBD), the Intergovernmental Panel for Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the United Nations World Ocean Assessment. Information on coastal and marine ecosystems is urgently required to address the UN Sustainable Development Goal (SDG) 14."

The authors apologize for these error and state that these corrections do not change the scientific conclusions of the article in any way. The original article has been updated.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00819/full#supplementary-material

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REVIEW
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Future Vision for Autonomous Ocean Observations

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Autonomous platforms already make observations over a wide range of temporal and spatial scales, measuring salinity, temperature, nitrate, pressure, oxygen, biomass, and many other parameters. However, the observations are not comprehensive. Future autonomous systems need to be more affordable, more modular, more capable and easier to operate. Creative new types of platforms and new compact, low power, calibrated and stable sensors are under development to expand autonomous observations. Communications and recharging need bandwidth and power which can be supplied by standardized docking stations. *In situ* power generation will also extend endurance for many types of autonomous platforms, particularly autonomous surface vehicles. Standardized communications will improve ease of use, interoperability, and enable coordinated behaviors. Improved autonomy and communications will enable adaptive networks of autonomous platforms. Improvements in autonomy will have three aspects: hardware, control, and operations. As sensors and platforms have more onboard processing capability and energy capacity, more measurements become possible. Control systems and software will have the capability to address more complex states and sophisticated reactions to sensor inputs, which allows the platform to handle a wider variety of circumstances without direct operator control. Operational autonomy is increased by reducing operating costs. To maximize the potential of autonomous observations, new standards and best practices are needed. In some applications, focus on common platforms and volume purchases could lead to significant cost reductions. Cost reductions could enable order-of-magnitude increases in platform operations and increase sampling resolution for a given level of investment. Energy harvesting technologies should be integral to the system design, for sensors, platforms, vehicles, and docking stations. Connections are needed between the marine energy and ocean observing communities to coordinate among funding sources, researchers, and end users. Regional teams should work with global organizations such as IOC/GOOS in governance development. International networks such as emerging glider operations (EGO) should also provide a forum for addressing governance. Networks of multiple vehicles can improve operational efficiencies and transform operational patterns. There is a need to develop operational architectures at regional and global scales to provide a backbone for active networking of autonomous platforms.

Keywords: autonomous and remotely operated vehicle, autonomous platforms, ocean observation, OceanObs'19, observing systems and networks, future vision

INTRODUCTION

In situ ocean observing is limited by the ability of humans to make comprehensive observations in many locations due to the remoteness, harshness, and sheer geographic dimensions of the ocean environment. In addition, the temporal scales cover many decades from seconds to years (Delory and Pearlman, 2018). *In situ* data with enough spatial and temporal resolution are needed for science to assist with resource stewardship and environmental management decisions that have wide social and economic impact (National Science and Technology Council, 2018). Knowledge gathering is limited by our ability to accomplish and sustain comprehensive observations in the ocean environment. Unmanned, autonomous, and remote sensing platforms are important tools to make the necessary observations possible. Application of these *in situ* observing capabilities must be done in a comprehensive manner, integrated with other elements of an ocean observing system, including satellite remote sensing and models. There are many tradeoffs among platforms when defining an observing mission. The trade-offs must take into account both science needs and societal needs; the United Nations Sustainable Development Goals (SDGs, United Nations, 2015) can help understand science and social needs. Quantifying the targets and indicators for the SDGs represent a global challenge for the science community to simultaneously enhance understanding of the oceans and to inform decision-making processes. Ocean observations and ocean science are a key to a sustainable future (Visbeck, 2018). The Framework of Ocean Observing (FOO, Lindstrom et al., 2012) uses requirement drivers, technology maturity, and societal impact to identify essential ocean variables (EOVs). Autonomous platforms already provide key observations for some EOVs. Further advances are now required in autonomous systems to meet the growing needs for ocean observing in biology (Boss et al., 2018; Lombard et al., 2019), biogeochemistry and ecology (Bange et al., 2019; Fennel et al., 2019; Jamet et al., 2019; Tilbrook et al., 2019), sea floor mapping (Wölfl et al., 2019), the deep ocean (Levin et al., 2019), the Arctic (Lee et al., 2017), and the increasing requirements for real-time data (Zappalà et al., 2016). New observation technologies and techniques will advance our understanding of the science and also address societal issues such as management of the energy, ecosystems, and raw materials of the ocean, and the ocean's impact on climate, weather, and food security.

To take the next steps in observing, we need more sustained and comprehensive measurements across spatial and temporal scales, and synoptic measurements across multiple scales. Information gaps occur in the deep ocean and under ice (Lee et al., 2017). There is still a vast need for better seabed mapping[1] (Mayer et al., 2018). Multiple anthropogenic impacts in ecosystem issues such as plastic debris are not quantified (Maximenko et al., 2019) as well as tracking of animal movement and migration. We need reduced data latency for things like biodiversity observations (Muller-Karger et al., 2018). Reduced data latency is also important for coastal water quality monitoring for environmental enforcement, for mitigating human impacts on marine animals such as endangered species in shipping lanes, and more efficient environmental management such as setting more optimal fisheries opening times and quotas. We need better, faster observations of transient events like harmful algal blooms (Anderson et al., 2019), tsunamis, underwater volcano eruptions, and gas hydrate plumes (Manalang et al., 2018).

Ship-based *in situ* ocean observations are increasingly limited by the cost of operating platforms that support the humans and instruments for detailed measurements (National Research Council, 2009). In addition, ship-based and manned submersible monitoring is limited in temporal and spatial coverage; however, ships provide great flexibility and are essential for servicing buoys and cabled observatories. Scuba diving offers limited reach into the ocean and is relatively risky. Remotely Operated Vehicles (ROVs) enable observations in more difficult environments at less risk to humans. ROVs are widely used in industry and military,[2] but they still require expensive platforms and human presence, and are, therefore, constrained to short-term operations in favorable weather conditions. Cabled observatories, which have the advantage of continuous operation and large power and bandwidth capabilities, are a valuable but expensive alternative for sustained observations and generally have limited geographic

[1] https://oceandiscovery.xprize.org/

[2] https://rov.org/market/

coverage. Moorings can be deployed in a wider range of locations with lower initial cost than fixed observatories but have telemetry limitations and high maintenance costs.

Unmanned Underwater Vehicles (UUVs) and Unmanned Surface Vehicles (USVs) are remotely operated platforms that allow more temporal and spatial coverage of measurements and sometimes lower cost, but they still depend on high-bandwidth communications or nearby manned support platforms for near-real-time control. Some platforms incorporate internal automatic control to increase mission times and reduce communication bandwidth or operational costs. These programmable, robotic vehicles have become known as Autonomous Surface Vehicles (ASVs) or Autonomous Underwater Vehicles (AUVs). ASVs and AUVs still communicate with operators through radio, satellite, or underwater acoustic signals, but their distinguishing characteristic is that they do not need humans to control them in real-time.

The early vision for autonomous platforms for ocean observations came from Stommel (1989) and Curtin et al. (1993), who envisioned large numbers of autonomous vehicles supporting comprehensive observations of the oceans. Curtin proposed that ocean observing is an integrated process of many different types of assets including vehicles and floats. The vision of the 1990s has evolved into modern capabilities. The Argo network (Jayne et al., 2017; Roemmich et al., 2019) has demonstrated the value of long-endurance autonomous platforms.

Autonomous Underwater Vehicles offer a real revolution in the marine technology field. They have become tools for solving a "wide range of issues in many theoretical and practical fields" (Gafurov and Klochkov, 2015). They have advanced in their payload capacity, computational capabilities, communication capabilities, and autonomy (Rudnick, 2016; Lee and Rudnick, 2018). Modular and reconfigurable systems will improve AUV flexibility and scalability. Increasing autonomy is a focus in the AUV community (Brito et al., 2019). Most current autonomous platforms operate, sample, and navigate according to a pre-programmed mission and in general are operated with some human 'supervision.' Only recently have such vehicles been deployed in fully autonomous mode. It is intended that future advanced autonomous platforms will be capable of adapting their parameters and algorithms, and they may choose actions or behaviors based on prior information or real-time collected data, to achieve a predetermined goal.

Intelligent platforms are only one part of a future vision. On-board sensing systems also play an important role (Delory and Pearlman, 2018). Mature sensors such as Conductivity, Temperature, and Depth (CTDs) are being fitted on a wider range of autonomous platforms. Optical imaging systems are becoming smaller and more efficient. A wide variety of optical sensors are available for biogeochemical measurements such as dissolved oxygen, alkalinity, and photosynthetically available radiation. Sensors are also available for biological measurements such as plankton monitoring. Active acoustic systems, such as multibeam, side-scan and sub-bottom sonars support hydrographic operations, biological and biomass studies, and subsea geological studies, while passive acoustic systems, including hydrophone arrays, have supported extensive work in mammal and fisheries research. There are still many types of sensors that cannot be fitted to platforms whose objective is to have endurance of months or years. The primary challenges for sensors lie in power consumption, size and stability over time (including issues of biofouling). Biological and biogeochemical sensors have posed the greatest difficulty.

Wave propulsion, variable buoyancy systems, and autonomous sailing have vastly extended the range of some types of platforms. Subsurface ocean observation and exploration remain fundamentally constrained by energy availability for propulsion, communication, and sensors. This energy bottleneck similarly limits real-time processing for autonomous systems and can be exacerbated by computationally intensive machine learning algorithms. Systems that can convert subsurface waves and currents to electrical power could play a significant role in meeting the energy needs of the next generation in autonomous technologies (Ayers and Richter, 2016).

This paper will look at the current state of the art and then address future visions for ocean observation and exploration using autonomous systems.

CURRENT STATE OF THE ART

Using the model of the Framework of Ocean Observing (FOO, Lindstrom et al., 2012), directions for advanced ocean observing are driven by societal requirements matched with observing system capabilities and maturity. Thus, the current state of the art forms a foundation for both the near-term missions and the vision for the next decade. **Figure 1** depicts some of the many elements of such systems. *In situ* sensing needs to be driven by specific requirements defined by ocean resource users, including industry, government and researchers who use ocean information. These needs span a full range of scales from global to local process studies, such as productivity of aquaculture and fisheries, management for sustainability or disaster mitigation. These all want more persistent, comprehensive coverage in time and space, with more temporal and spatial resolution than presently possible. This is a natural fit with the evolving autonomous system capabilities.

Standards and Best Practices

With the scales of the oceans, an important step forward for autonomous vehicles (and for the whole of ocean observing) is to have significantly improved interoperability of sensors, systems and data. Increased cooperation across system elements was noted as a benefit of GOOS and an important aspect in planning for the next decade (Tanhua et al., 2019). It has also been recognized that standards and best practice methodologies support interoperability and reproducibility. These methodologies make it easier to operate efficiently, share results and leverage existing data. Standards and best practices should be readily available and encouraged for broad adoption in ocean observing including autonomous vehicles. New capabilities should conform to current standards and best practices where possible or systematically develop new ones where needed as

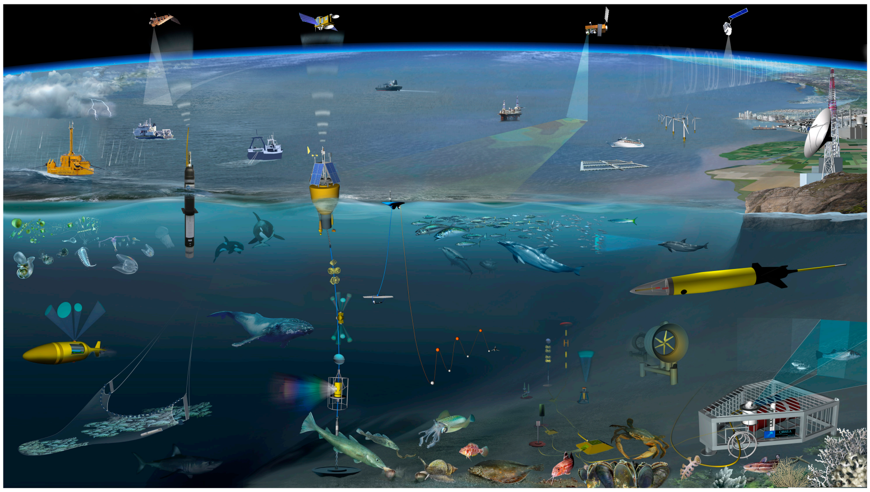

FIGURE 1 | A depiction of the many autonomous and remote sensing platforms that comprise an ocean observation system (source: Glynn Gorick and the NeXOS project).

part of routine operating procedures. With the role that they can play in the coming decade, this section on standards and best practices was included in our review and vision of autonomous vehicles.

Best practices and standards are the two most common forms of documenting methods. They are part of a continuum of community agreements (Pulsifer et al., 2019). Best practices, in the way we use them in this paper, are descriptions of methods, generally originated bottom-up by individual organizations, that are widely adopted. They can come in many forms such as "standard operating procedures," manuals or guides. The definition of a best practice for ocean observing is: "a best practice is a methodology that has repeatedly produced superior results relative to other methodologies with the same objective; to be fully elevated to a best practice, a promising method will have been adopted and employed by multiple organizations" (Simpson et al., 2018). This definition is like that used in other fields for best practices (Bretschneider et al., 2005). They all have the objective of improving the quality and consistency of processes, measurements, data and applications. The identification of a "best practice" is not easy and may engender controversy. Two options are under consideration for such a designation. Either broad uptake (multiple organizations) or recognition by an expert peer panel. In either case, the term "fit for purpose" must be acknowledged as what is best for one objective (e.g., tropical arrays) may not be best in another environment (e.g., Arctic under ice monitoring) (Simpson et al., 2019).

Standards have the same objectives as best practices; the difference is that standards may serve as benchmarks for evaluation in addition to being processes. Also, they are generally top-down and may become mandatory legislated standards, such as the European INSPIRE[3] legislation. The International Standards Organization (ISO) defines standards as "documents of requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose." The time for the formation of a standard by a Standards Development Organization (SDO) is 3–5 years or more using formal working groups to write the standard.

Best practices can address the elements that make up the flow from observations to applications. This flow is called the "value chain" for ocean observing, which derives from the original work of Porter (1985). Ideally, the best practices for each of the value chain elements have defined interfaces so that they can be linked.

An example of such linking is seen in recent Open GeoSpatial Consortium (OGC) standards for describing, connecting, and controlling sensor networks. Standards such as OGC's Sensor Markup Language, Sensor Planning Service, Sensor Web Enablement, and SensorThings[4] all support this emerging trend. However, human contributions will not be entirely replaced, as there are elements of quality assurance and data integration into both models and products that will need human participation. For both machines and humans, there is a need for defined methodologies in the form of best practices and standards (Pearlman et al., 2019).

For ocean observing, a sustained Ocean Best Practices System has been implemented to make methods readily available to support sensor and platform applications, as well as other elements of the end-to-end value chain of ocean observing (Pearlman J. S. et al., 2017).

Sensors

The heart of any observation system is its sensors. The variety of sensors used on autonomous platforms has been growing for more than two decades (Schofield et al., 2010; Tintoré et al., 2013; Marques et al., 2018; Testor et al., 2018). These capabilities are driven by the need to characterize the ocean comprehensively and in near real-time (Zappalà et al., 2016).

[3]https://inspire.ec.europa.eu/inspire-legislation/26

[4]http://docs.opengeospatial.org/is/15-078r6/15-078r6.html

Choosing sensors for a mission is not always straightforward. Sensor systems can have different maturities, form factors, power requirements, and trade-offs between accuracy, resolution, stability, and sampling frequency.

This paper focuses on sensor technologies that have matured recently or are still maturing in autonomous vehicles applications. Sensors that have reached a high level of maturity—or a high Technology Readiness Level (TRL, Mankins, 1995)—are covered in less detail. There are important physical oceanographic sensors that are at a high TRL, such as CTD sensors, active acoustic sensors, and several optical sensing techniques for chemical compounds. The optical sensors increasingly use integrated light-emitting diodes (LEDs), lasers, and optical spectrometry technologies. Conversely, most sensors for biogeochemistry and biological compounds are at a lower TRL. Biogeochemical sensors (BGC) are used on some autonomous platforms such as gliders and profiling floats, and there is a new BGC component to the Argo program (Johnson and Claustre, 2016). More sophisticated BGC sensors for nutrients, such as Lab-on-Chip, are not ready for routine operations. Biological sensors are less mature than BGCs, but they offer opportunities for significant advancement.

Physical Oceanographic Sensors

Conductivity, temperature, and depth sensors have been in use for many decades, suspended on mooring lines, mounted to ship-board rosettes, and integrated into AUVs. The salinity calculation (McDougall et al., 2009) is important for deriving water density and is heavily dependent on concurrent pressure and temperature. Physical water-transport lags between sensors can create errors in profiling floats or gliders moving at speeds of 0.5 m/s in the presence of sharp vertical temperature gradients (Garau et al., 2011). Sensors on autonomous platforms can also measure physical variables, such as current velocity. Acoustic Doppler Current Profilers (ADCP) are widely used on research vessels, moorings, and more recently on AUVs including gliders (Thurnherr et al., 2015) although they are not routinely installed on gliders because of power requirements and data processing challenges (Hall et al., 2019).

Autonomous Underwater Vehicles have been fitted with multi-beam echosounders, sidescan sonars, and sub-bottom profilers (Nakamura et al., 2013; Thompson et al., 2015; Blomberg et al., 2017). The weight and power requirements of these sensors demand large AUVs that have short endurance and require research vessel support, but they have still proven the concept of automating some survey applications. Better navigation, positioning, and geo-referencing is needed for some high-resolution surveys to be completed with autonomous systems instead of survey vessels (Kunde et al., 2018).

Biogeochemical Sensors

Optical sensing also addresses biogeochemical parameters in the marine environment (Moore et al., 2009). There are many types and many applications of optical sensors for chemistry and biology. Nutrient cycles (nitrate, phosphate, and silicate) participate in carbon dioxide (CO_2) sequestration in the ocean and are linked with the global carbon cycle. Observing their concentration in the open and coastal ocean will allow us to better understand the major biogeochemical cycles.

The optode sensor is now commonly used to measure oxygen (Bittig et al., 2015, 2018) and there is also work to further extend these sensors to measure CO_2 (Atamanchuk et al., 2014; deYoung et al., 2018). These sensors are small, operate at low power and have good stability for multi-year deployments. The stability characteristics for the CO_2 version of the sensors have yet to be demonstrated. Another approach to measuring CO_2 is through pH, which requires some knowledge of how alkalinity relates to CO_2 but avoids direct measurement of CO_2. The development of pH sensors was stimulated by the Schmidt X Prize (Okazaki et al., 2017) with the result that there are now pH sensors ready for deployment on Argo Floats (Xing et al., 2018) and testing is underway for operation of pH sensors on underwater gliders (Saba et al., 2018).

Colorimetric detection is a method of determining the concentration of a chemical element or compound in a solution using a color reagent. The most widely used method to detect nutrients is based on colorimetric detection using traditional, discrete shipboard-sampling techniques and onboard analyses (Ma et al., 2014). Over the past decade, significant progress has been made in developing *in situ* nutrient sensors, and a few are commercially available to measure nitrates, phosphates, and silicates (Legiret et al., 2013; Worsfold et al., 2016). For autonomous operations, using reagents introduces challenges. The reagents must be replenished regularly, their stability is of concern, their cross calibration with standards needs to be done, and they have potential limitations from chemical interferences and refractive effects (McKelvie et al., 1997). Optical sensors can also measure alkalinity (pH), using a pH-sensitive dye and a wide-band emission LED. The technique is straight forward but sensitive to temperature, which can cause significant errors if the seawater temperature differs significantly from that of the sample container. Automated sensors have been demonstrated on the NeXOS project (Pearlman J. et al., 2017) and others. However, the sensor design for autonomous platforms with low power and compact size is still in development (Precheur and Delory, 2018).

Direct optical measurements can overcome many of these concerns. Woods Hole Oceanographic Institute (WHOI) pioneered this with the *In Situ* Ultraviolet Spectrophotometer (ISUS), which uses ultraviolet illumination and analyzes the absorption characteristics of a water sample with a spectrophotometer (Johnson and Coletti, 2002). The technique is applicable to compounds of interest to aquatic scientists, including nitrate, nitrite, bisulfide (HS^-) and bromide. Subsequent sensors have operated on the Argo profiling floats (Johnson et al., 2010) and are available commercially.[5] Raman spectroscopy has been demonstrated *in situ* (Hu and Voss, 1997), and used to identify deep-sea geochemistry with ROV-mounted instrumentation, but these sensors are very heavy, require a lot of power, and precise physical alignment with bottom samples (White et al., 2004; Zhang X. et al., 2012). Other biogeochemical sensors are at lower maturity levels that

[5]https://www.seabird.com/nutrient-sensors/suna-nitrate-sensor/family?productCategoryId=54627869922

have interesting potential, for example, the series of Lab-on-Chip systems that are relatively compact packages and can operate autonomously (Mowlem et al., 2018).

Small packaged radiometers for directly measuring photosynthetically available radiation (PAR; 400–700 nm), and for measuring upwelling and downwelling spectral irradiance and radiance (tunable for multiple discrete wavelengths) are very useful measurements to characterize several parameters in near-surface waters. They are typically used to quantify the absorption, scattering and other optical properties of the water, including color observed from above the surface (water-leaving radiance and reflectance). These observations are used in the vicarious calibration of sensors on satellites, aircraft, and other platforms designed for the remote sensing of phytoplankton biomass and water quality parameters. Many water quality assessments require turbidity and underwater visibility observations. Phytoplankton, biomass, species composition, and indicators of primary production (PP), a measure of carbon uptake by phytoplankton, are related to the underwater light quality (color) and quantity. Several studies involving gliders and Argo floats have demonstrated estimation of parameters related to water quality and phytoplankton abundance and distribution from PAR and concurrent BCG and physical EOV observations (Hemsley et al., 2015; Pascual et al., 2017).

There are several commercially available *in situ* fluorometers, which address parameters from bacterial components to chlorophyll and from fluorescent dissolved organic matter (FDOM) to polycyclic aromatic hydrocarbons (PAHs). Measurements based on the principle of fluorescence, the emission of light at a wavelength different than the excitation wavelength, are sensitive and specific. Fluorometers may operate with a single or with multiple stimulation wavelengths and monitor one or more emission wavelengths (Alexander et al., 2012; Ferdinand et al., 2017). A recent development and example of a state-of-the-art capability is the MatrixFlu, which is a compact optical multifunctional sensor developed within the NeXOS project (Pearlman and Zielinski, 2017). An ultraviolet (UV) version of the MatrixFlu senses fluorescent-dissolved organic matter and PAHs using three dedicated UV excitation wavelengths and four detection channels in an ultra-compact seawater-resistant housing. The unit has been tested in ASVs and AUVs. A version with visible LEDs is commercially available.[6]

A more sophisticated capability is underwater mass spectrometry (Short et al., 2018). This technique can do elemental and isotopic analyses including identifying and describing compounds. The advent of miniature components, such as vacuum pumps, 20 years ago stimulated the creation of portable mass spectrometers (Short et al., 1999) that can be hosted on autonomous platforms such as AUVs (Chua et al., 2016). These portable units provide local and near real-time analyses of analytes, allowing new insights in water mass characterization. While they are powerful tools, they are challenging to using on power-limited platforms. They need an internal vacuum for the mass spectrometer to operate. Also, a methodology for introducing samples into the vacuum from the high pressures at depth is required. This is done typically using membrane introduced mass spectroscopy (MIMS, Johnson et al., 2000), which works for light stable gases (e.g., O_2 and CO_2) and volatile organic compounds. Additionally, a means for ionizing the sample gas is required. For underwater systems, this is done by electron impact using a hot filament to do the ionization. The electrical power requirements for the vacuum pump and the ionization are not negligible, typically 50–100 W, and future efforts are to reduce the power and size of these systems. Regardless of the challenges, there have been both feasibility demonstrations and practical applications with the spectrometer mounted on AUVs, ASVs, and tethered systems. In a demonstration, a spectrometer operating on an AUV surveyed downstream of the Deepwater Horizon spill (Camilli et al., 2010).

Biological Sensors

Optical sensors have high potential for cost-efficient sensing of the ocean environment. Collecting both still and video images is inexpensive, easier, and more accessible to a broader range of researchers in earth observing (Underwood and Marouchos, 2017). Miniature, low-power, image capture systems can collect increasingly detailed imagery of marine organisms and habitats, including those in the deep sea (Johnsen et al., 2013; Kwasnitschka et al., 2016), although autonomous systems still do not match the capability of towed systems (Purser et al., 2019). Imaging data are increasingly used for habitat assessments and studies (Davie et al., 2008; Kocak et al., 2008) of status and trends in species distribution and abundance. Stereo and multi-camera imaging and underwater light detection and ranging (LIDAR, Sasano et al., 2016) also enable increasingly quantitative levels of imaging that help us better understand environmental variability and changes over time (Mortazavi et al., 2013). There are eye-safe LIDAR systems for classifying marine life based on imagery (Cao et al., 2017). LIDAR systems have become more ubiquitous for sensing suspended particle fields, solid objects, and surface characteristics (Wedding et al., 2019). As these systems become more widespread, so has the need for extensive data support systems to store and process large data sets (Pirenne et al., 2015).

A major area of biological observations is monitoring of plankton. Many sensors, instruments, platforms, and methods available for *in situ* operational observations of plankton (Boss et al., 2018; Lombard et al., 2019). The goal of observing plankton is to better understand the basis of the food chain, which is responsive to changes in the environment due to natural abiotic and biotic forcing and due to direct human pressures, such as fisheries, other extractive practices, and pollution (Muller-Karger et al., 2014; Muller-Karger et al., 2018). Sampling plankton over high spatial and temporal resolution and across several size classes from microns to millimeters has been demonstrated in many locations around the world.

Zooplankton imaging is now also possible with several devices (Cowen and Guigand, 2008; Picheral et al., 2010). Active acoustics can be used to look at biomass, including plankton (Benoit-Bird and Lawson, 2016), but more detailed analyses of individual cells are done with flow cytometers (Brownlee et al., 2016; Hunter-Cevera et al., 2016). The imaging flow cytobot (IFCB) (Sosik and Olson, 2007) developed by WHOI is an example of a

[6]https://www.trios.de/en/matrixflu-vis.html

commercially available system[7] that has been modified to work in autonomous vehicles. Its size and depth limitations (102 cm length and 40 m maximum depth) generally makes it usable on ASVs. A comprehensive review of other sensors for monitoring plankton illustrates the many alternative techniques and their commercial availability (Lombard et al., 2019). What is notable in that summary and the literature of sensor providers is the increasing interest and capability for operations on autonomous vehicles. Examples are the IFCB by McLane Labs, the LISST-200 by Sequoia,[8] and the UVP6-LP by Hydroptics.[9]

An emerging field for marine biological assessment is nucleic acid analysis, especially the use of environmental DNA (eDNA). The number of sensors demonstrating successful eDNA detection has increased rapidly in recent years, for example MBARI's Environmental Sampling Processor (ESP) (Beja-Pereira et al., 2009; Foote et al., 2012; Scholin et al., 2017). This detection method has become an effective tool for genetically monitoring species presence and extending the work to address abundance, diversity, and functionality of both microbes and higher organisms (Thomsen et al., 2012; Scholin, 2013; Kelly et al., 2014). This evolution has led to new studies of ecology and a framework for understanding this ecology (Barnes and Turner, 2016). One challenge in these applications is in building eDNA analysis systems that can work on autonomous vehicles; however, recent steps toward a full *in situ* eDNA measurement system on board an autonomous vehicle involves collecting and preserving samples for laboratory analysis (Scholin et al., 2017; Birch, 2018; Evans et al., 2019).

Acoustic systems have long been used to enable short- and long-range observations in the ocean (Howe et al., 2019). They are becoming more prevalent on a wider range of research vessels, autonomous systems, and even a range of ocean animals (Johnson and Tyack, 2003; Heupel et al., 2018) because of smaller and lower-power sensors. Acoustic systems can also be combined with optical systems to allow for qualitative and direct ground truthing of acoustic data for both hydrographic and biomass applications (Sherlock et al., 2010; Underwood et al., 2015; Marouchos et al., 2016).

Sound is recognized as an Essential Ocean Variable[10] (EOV, Miksis-Olds et al., 2018). Capturing and analyzing ambient sound-fields over long periods reveals a great deal of information about ocean dynamics and human activity. Anthropogenic sounds of concern include shipping noise, seismic exploration, dredging operations, oil and gas surveys, naval sonars, and marine construction noise. Natural sounds of interest include those from biotic sources such as animal vocalizations and abiotic sources such as underwater earthquakes. The acoustic landscape, known as the soundscape (Krause, 1993), is the combination of all sounds perceived by an animal or recorded by an instrument. Passive Acoustic Monitoring (PAM) is commonly used for studying marine fauna, for quantifying ambient sonic characteristics of marine environments, and for assessing the impacts of anthropogenic disturbances. In bioacoustics, PAM is typically used to complement visual monitoring, and in the dark or in bad weather it is the primary monitoring method (Erbe et al., 2016b). PAM applications in bioacoustics include presence/absence monitoring and density estimation of marine fauna (Marques et al., 2009, 2011), soundscape assessments (Erbe et al., 2016b), and biodiversity assessments (Parks et al., 2014). PAM is also an attractive choice for monitoring various anthropogenic events (Erbe et al., 2016a) and geophysical events, such as undersea eruptions and quakes (Sukhovich et al., 2014), sea-surface wind and precipitation in remote regions (Nystuen et al., 2000), and, most notably, monitoring violations of the Comprehensive Nuclear-Test-Ban Treaty (Hanson et al., 2001). Sound is also used to diagnose engineering issues (Boyd and Varley, 2001; Jirarungsatian and Prateepasen, 2010).

Since passive acoustic systems do not emit sound, they are easier to deploy in protected areas and in other situations where this feature is valuable. Commonly, acoustic data are collected using cabled or moored underwater recording equipment that can be deployed for extended periods. Data are also collected *in situ* using equipment onboard ships or by surface drifters and AUVs. The collected acoustic data are analyzed onsite or offsite, by manual or automatic methods, to detect sounds of interest. Analysis of acoustic data often employs *a priori* knowledge of sound-to-source associations obtained from visual or other means. Human interpretation is usually needed to make inferences from the recorded events. Automation is a continuing challenge.

Passive Acoustic Monitoring benefits directly from the continued independent advancements in sensor technology, smaller and lower-power electronics, and the transition to high-capacity solid-state data storage media. Current autonomous recorders have low power consumption, reduced internal noise, greater durability, and faster data-transfer between system components. Lower-cost devices are being designed to integrate with ocean observing systems (Toma et al., 2015; Pearlman J. et al., 2017). Developing pattern recognition algorithms has evolved from employing purely deterministic methods to using statistical learning methods that offer more generalized results. Algorithm development cycles have been significantly sped up by hardware advancements and the relative ease of building models for statistical learning. The use of Artificial Neural Network (ANN) based methods, such as Convolutional Neural Networks (CNNs) and Deep Neural Networks (DNNs), is increasing.

Platforms

Autonomous platforms are making measurements over a wide array of spatial and temporal periods. Observations range from large-scale processes to small-scale variabilities in salinity, temperature, nitrate, pressure, oxygen, biomass; and many other parameters, depending on the needs of the user. Autonomous technologies for ocean observations in use today include aerial, surface, and subsurface vehicles, satellites, buoys, subsea moorings, and bottom nodes. Observation systems can use any or all of these elements (Kadiyam et al., 2015). True autonomy is still unavailable; all these observation systems still require a great deal of human interaction and support (Ramp et al., 2009).

[7]https://mclanelabs.com/imaging-flowcytobot/

[8]https://www.sequoiasci.com/product/lisst-200x/

[9]http://www.hydroptic.com/index.php/public/Page/product_item/UVP6-LP

[10]http://www.goosocean.org/eov

The largest platforms now support payloads that many years ago would have required manned research vessels. These platforms are still quite expensive and complex. Conversely, systems of numerous, small, and inexpensive observing platforms can increase spatio-temporal coverage, but only for a limited number of ocean variables because small size and limited power implies a limited scientific payload. See Verfuss et al. (2019) for a more detailed review of platforms and their applications.

Surface Vehicles

There is a long history of autonomous surface vehicle development (Manley, 2008) and in recent years a wide proliferation of ASVs, particularly conventionally powered designs based on hulls similar to small manned vessels (Liu et al., 2016). ASVs are starting to be adopted in industrial and military applications for hydrographic surveys,[11] inspection, mine countermeasures, and weapons target practice. Such conventional ASVs can support small- to medium-sized payloads and have endurances of hours to weeks, similar to the conventional vessels they replace.

Autonomous Surface Vehicles that use wind- or wave-power to extend endurance have matured recently and are beginning to be applied in ocean observations. The Sailbuoy (Ghani et al., 2014; Hole et al., 2016) and Saildrone (**Figure 2**) (Meinig et al., 2015; Mordy et al., 2017) are propelled by wind, while the Wave Glider^{TM} (Daniel et al., 2011) and Autonaut use wave power for propulsion. Because of their surface expression, ASVs developed for long-term data collection often use solar panels to extend mission durations, which can be up to 1 year (Villareal and Wilson, 2014), supporting payload power budgets on the order of 30 W. Some ASVs have been fitted with acoustic sensors for bathymetric surveys[12] or measuring current velocity and biomass,[13] as well as BGC sensors to study upwelling and frontal region dynamics[14] (Chavez et al., 2018) and measure carbon exchange between ocean and atmosphere.[15] Long-endurance ASVs are also envisioned as communication relays for other subsea platforms (German et al., 2012; Ludvigsen et al., 2016; Phillips et al., 2018).

Buoyancy Engine Vehicles

Buoyancy engine platforms include drifters such as Argo floats, and gliders such as SeaGlider and Slocum. Low power requirement of the buoyancy engine along with relatively small, low-power payloads have enabled long endurance missions. Long endurance reduces operational costs and small size reduces the need of large vessels for deployment/recovery operations.

Argo floats have become a workhorse of global ocean observations, providing key measurements of the ocean over the past two decades (Riser et al., 2016). Gliders are widely used for physical oceanographic measurements, especially to study dynamic processes in shallow and coastal areas not well covered by Argo (Liblik et al., 2016; Rudnick, 2016). They are also finding use in military and industrial applications, such as oil and gas production.

It is because of their long endurance and small size that these technologies could be deployed at the global scale by the scientific community in the framework of the Global Ocean Observing System (GOOS), particularly with Argo and the related Deep-Argo, Argo-BGC (Roemmich et al., 2019) but also with the OceanGliders network (Testor et al., 2019).

There are efforts to increase the payload capacity of gliding designs, for example by using blended-wing designs as shown in **Figure 3** (D'Spain, 2009), but these have not yet been widely adopted.

There has also been some work to integrate a buoyancy engine into a surface craft. The Ocean Aero was the first such Unmanned Submersible Surface Vehicle (USSV). Ocean Aero is not really intended for underwater sampling but rather to dip just below the surface to avoid detection and to get away for surface waves. Rather than use a buoyancy engine, the Ocean Aero essentially operates as a submarine pumping air and water. The SeaDuck (Bachmayer et al., 2018) does use a 4 L buoyancy engine that enables the vehicle to reach depths of 200 m. At the surface SeaDuck operates with a thruster with intended surface operational speeds of 2 m/s.

Thruster-Driven Subsurface Vehicles

Conventional AUVs are typically propeller driven and provide stable platforms for applications such as high-resolution seafloor mapping and imaging. These systems are most often deployed with a supporting surface vessel due, in part, to navigational requirements and frequent recharging/data download.

Autonomous Underwater Vehicles are increasingly used to map or monitor changes in remote ecosystems challenged by pollution, global warming, ocean acidification, and invasive species (Zhang Y. et al., 2012). Industrial activities such as oil and gas production primarily use remotely operated vehicles (ROVs) rather than autonomous platforms like AUVs. However, there are growing industry investments in autonomous systems for routine inspection and intervention activities, which promise to reduce long-term installation maintenance costs by taking on tasks previously requiring manned vessels and ROVs.[16] Improvements in AUV monitoring and emergency systems are increasing platform reliability and mission success rate (Inzartsev et al., 2016).

Autonomous Underwater Vehicles range in size from hand-deployable to approaching the size and capability of a small manned submarine (Coly, 2016). Conventional designs, such as Hugin, Autosub (Roper et al., 2017), REMUS, Sentry (Kaiser et al., 2016), and Tethys (Hobson et al., 2012), support payloads of hundreds of watts to nearly full-ocean depth, with typical endurances of days to weeks. In some cases, design endurances

[11]https://www.hydro-international.com/content/article/bering-sea-asv-force-multiplier

[12]http://www.imr.no/en/hi/news/2019/april/sends-saildrone-cruising-in-the-north-sea

[13]https://www.fisheries.noaa.gov/feature-story/saildrone-launch-begins-test-improve-west-coast-fisheries-surveys

[14]https://podaac.jpl.nasa.gov/Saildrone

[15]https://www.saildrone.com/news/usv-study-carbon-uptake-southern-ocean

[16]https://www.maritime-executive.com/article/growing-interest-in-auvs-for-oil-and-gas

FIGURE 2 | SailDrone deployment in Norway (source: Erlend A. Lorentzen/Institute of Marine Research).

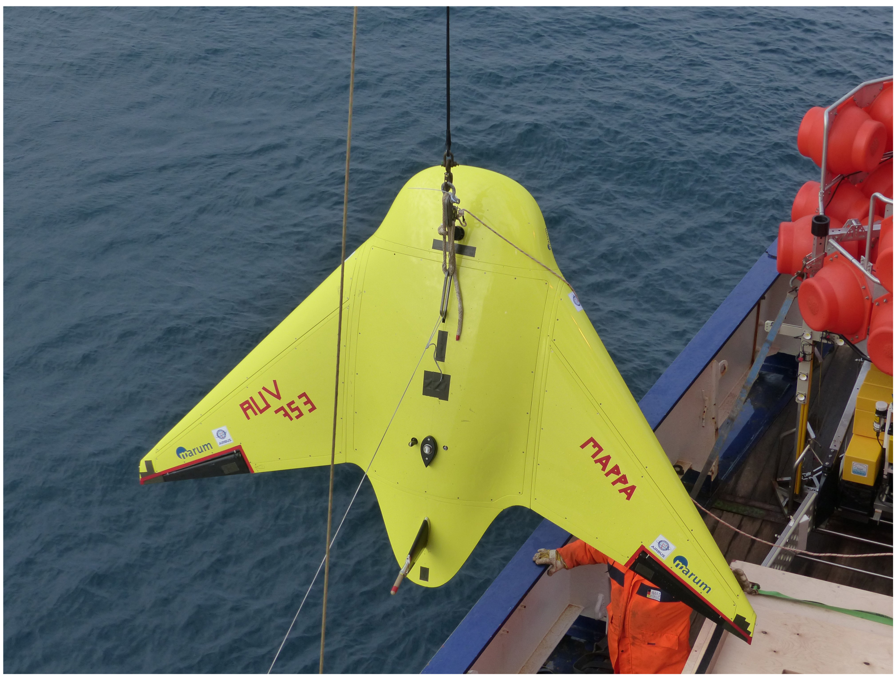

FIGURE 3 | The Blended-Wing glider designed as part of the ROBEX project (© Christoph Waldmann, MARUM, a cooperation project between MARUM and Airbus with support by MBARI).

are many months. Wynn et al. (2014) and Vedachalam et al. (2018) review the capabilities of AUVs.

Conventional designs typically require forward motion for control, but some designs called hovering AUVs or over-actuated AUVs (such as Delphin2 and ARTEMIS, **Figure 4**) have precise station-keeping for tasks such as inspection (Philips et al., 2013; Albiez et al., 2015). Conventional AUVs such as REMUS have also been experimentally fitted with such capabilities (Packard et al., 2010). Intervention AUVs build upon the capability of hovering AUVs to add manipulator arms and other devices to begin to match the capability of ROVs (Ridao et al., 2015).

The diversification of hybrid underwater vehicles is extending our ability to monitor our environment. Equipping gliders with thrusters enables them to overcome some environmental

FIGURE 4 | Stone Aerospace's ARTEMIS vehicle being launched into the Antarctic ocean through a drilled hole.

limitations, while adding buoyancy engines to a conventional AUV can reduce the energy needed to maintain depth, which increases range and endurance compared to solely using propeller propulsion (Sauser, 2010). Similarly, combining the type of platform stability and manipulation capabilities typical of ROVs with AUV platforms offers significant opportunities for close-up observations, sampling, and infrastructure maintenance that was previously only possible with ship-supported ROVs (Johansson et al., 2010).

Energy Sources

As noted previously, energy limitations can impact the mission capabilities of autonomous vehicles. There have been significant successes in increasing the endurance of autonomous underwater vehicles because of advances in vehicle design, power management, and chemical energy storage. For example, lithium-seawater batteries have an energy density up to 4 MJ/kg, twice that of primary lithium-ion batteries and almost an order of magnitude higher than rechargeable lithium-ion batteries (Davis and Sherman, 2017; Roper et al., 2017). These improvements have extended time between maintenance intervals, increased potential for onboard computing (e.g., enabling adaptive sampling), and expanded payloads to include sensors with higher fundamental power consumption. Propeller-driven AUVs cruising at up to 1 m/s now have endurance design targets exceeding 6,000 km (Roper et al., 2017) and support a variety of sensors from low-power measurements of water properties to more power-intensive multibeam sonars (Hobson et al., 2012; Wynn et al., 2014). However, maximum payloads remain limited compared to surface vessels (e.g., <1 m^3), and increasing payload size increases propulsive power requirements and overall vehicle costs. Given the limits to propulsive efficiency (Phillips et al., 2017), there remains a significant gap between the payloads that can be supported by a manned or autonomous surface vessel and those that can operate autonomously underwater for extended periods. Similarly, "high" power consumption for sensors is on the order of 10 W (Hobson et al., 2012; Roper et al., 2017), which is still quite low in absolute terms compared to what is possible for cabled observations. One way to extend endurance and capability without increasing vehicle cost is for vehicles to dock at a recharge node. This is an emerging technical capability that has achieved some success in limited, short-term demonstrations (Cruz et al., 2017; MBARI, 2018). If a recharge node can be shared among many vehicles, the savings in vehicle costs may offset the capital and operational cost of the recharge node. The gains from moving to this operational model are potentially transformative if observational requirements are compatible with the platform density and mission profiles needed to realize the operational cost savings.

Such a capability requires an external power source. Candidates include diesel-fired engines and fuel cells, which can produce electrical power from fuels with an order of magnitude higher energy density than batteries (e.g., 38–48 MJ/kg for diesel, 142 MJ/kg for hydrogen). However, these recharge systems themselves require periodic refueling and a surface expression for the reaction oxidant (i.e., air). In some situations, particularly for sub-surface applications, harvesting *in situ* energy resources is a compelling alternative to chemical energy conversion. *In situ* harvesting has already enabled substantial advances in endurance using wave propulsion (e.g., Wave Gliders^{TM}, Webb et al., 2001) or wind (e.g., Saildrones, Mordy et al., 2017); however, it remains uncommon for energy harvesting to provide subsurface propulsion or meet electrical demands posed by remote sensing, onboard processing, and communication. If we restrict our consideration to instrumentation nodes that also provide recharge and communication services to AUVs, this application will likely require the equivalent of 100 W to 10 kW of continuous electrical power. This likely eliminates some conversion technologies that are feasible only at much smaller scales, such as vibration energy harvesting (Beeby et al., 2007). The most probable near-term *in situ* candidate energy sources include the following:

- Solar photovoltaic panels (Razykov et al., 2011);
- Wind turbines, either horizontal axis or vertical axis (Sun et al., 2012);
- Wave energy converters, which convert the kinetic and/or potential energy in surface waves to electricity (Falcão, 2010);
- Current turbines in tidal or ocean currents, which operate on a similar principle to wind turbines (Khan et al., 2009); and
- Thermal gradient energy conversion from thermal vents (Xie et al., 2016), on a similar principle to larger-scale ocean thermal energy conversion (Vega, 2002) or smaller-scale harvesting from profiling platforms.[17]

Table 1 enumerates these technologies, their resource intensities, conversion efficiencies, benefits, and challenges. A key challenge is that conversion technologies that are currently commercially available require a surface expression, which can be difficult to maintain; however, adopting pre-commercial technologies does not lie in the far future. For example, small wave energy converters have been used to provide power to navigation buoys for some time (Masuda, 1986). Recently, the Monterey Bay Aquarium Research Institute (MBARI) developed an AUV recharge station associated with a buoy acting as a wave energy converter (Hamilton, 2017; MBARI, 2018). In another recent example, a joint industry project involving academic researchers and a wave energy technology developer deployed an autonomous package consisting of a wave energy converter and integrated instrumentation package (Joslin et al., 2019). The instrumentation package includes stereo optical cameras, artificial illumination, a multibeam sonar, acoustic camera, and two hydrophones. Data are continuously acquired from all instruments and processed in real time by an onboard computer to determine if they include events of interest, for example marine mammal presence. In addition, the project is demonstrating the longevity of a wireless power transfer solution for AUV recharge. The entire system required 600 W of continuous power, which was produced primarily by the wave energy converter with a backup solar panel (enough to maintain the "heartbeat" on the programmable logic controller and communication link) via a battery-backed microgrid.

Adopting wave, current, and thermal gradient technologies has been slow in grid-connected markets due to their cost substantially exceeding that of renewable alternatives such as solar and wind; however, there is growing global recognition that the grid is not the sole market for these technologies (Copping et al., 2018). Numerous technology developers creating wave energy converters are sizing and tuning their devices to serve smaller markets including ocean sensors (e.g., Resen Wave in Denmark). Recent research has produced an order-of-magnitude gain in the

[17] https://medium.com/dissected-by-propel-x/thermal-recharging-technology-a-game-changing-clean-energy-source-e6002279615a

TABLE 1 | Candidate energy sources for AUV recharge and offload nodes.

Energy source	Primary resource intensity	Conversion efficiency (%)	Benefits	Challenges
Solar photovoltaic	90–350 W/m^2 panel area[a]	10–40[b]	• Commercial technology • Unlimited persistence	• Limited resource at high latitudes • Harsh operating environment for surface expression
Offshore wind	40–800 W/m^2 rotor swept area[c]	15–45[d]	• Commercial technology • Unlimited persistence	• Limited resource at equatorial latitudes • Harsh operating environment for surface expression • Small-scale, distributed wind systems have lower efficiency
Wave	10,000–120,000 W/m of linear wave crest[e]	10–100+[f]	• Unlimited persistence • Does not require a surface expression	• Pre-commercial technology • R&D has been focused on grid-scale applications
Ocean currents	60–4100 W/m^2 rotor swept area[g]	15–45[h]	• Unlimited persistence • No surface expression	• Pre-commercial technology • R&D focused on grid-scale applications • Limited geographic relevance
Thermal gradients	–[i]	–[i]	• Unlimited persistence • Does not require a surface expression	• Limited resource at high latitudes • Environments near thermal vents are extremely harsh

[a]Direct normal radiation: https://power.larc.nasa.gov/data-access-viewer/. [b]Razykov et al. (2011). [c]Estimated from annual average wind speed at 10 m: https://power.larc.nasa.gov/data-access-viewer/. There is a substantial reduction in the resource with proximity to sea surface due to logarithmic wind profile. [d]Lower end corresponds to turbines with passive control systems; upper end corresponds to turbines with active control systems: (Manwell et al., 2010). [e]Gunn and Stock-Williams (2012). [f]Conversion systems radiate waves and can, in theory, capture energy beyond their physical extent. Range corresponds to small-scale systems at the lower end and theoretical performance on the upper end. Ranges for grid-scale wave energy conversion technologies fall between these extremes and are discussed in Babarit et al. (2012). [g]Range corresponds to 0.5–2.0 m/s current speed and are representative of energetic ocean currents. Power varies with the cube of velocity, so currents weaker than 0.5 m/s are generally unsuitable for energy harvesting. [h]Assumed identical to the value for wind, given the potential for ocean current technologies to leverage technology experience for wind. [i]Theoretical thermal conversion efficiency is given as $1 - T_L/T_H$ where T_L is a low-temperature reservoir (e.g., cold seawater at depth) and T_H is the high-temperature reservoir (e.g., thermal vent, warm seawater near the surface). Energy yield depends on rates of heat transfer.

conversion efficiency of wave[18] and current (e.g., Strom et al., 2017) systems suitable for integration with autonomous observing systems. Developing marine energy conversion technologies for ocean observation and exploration markets would also be mutually beneficial, allowing rapid iteration of prototypes at smaller scale, the demonstration of novel deployment and maintenance strategies, and opportunities for mass production.

Communications

It is common to use satellite communications for autonomous systems that have some type of surface access (Krishfield et al., 2008; Roemmich et al., 2009; Daniel et al., 2011). The bandwidth is typically on the order of hundreds of bytes per second, which is suitable for command and control, but only some types of direct measurements.

Underwater communication is difficult because of the nature of ocean physics. For acoustic communication, channel estimation and choice of sensor locations are both difficult because of multipath and fluid motion effects. For electromagnetic communication the limitation is the absorption of electromagnetic energy in water.

Acoustic communication is used for low data rates and medium distances, and NATO recently published an international standard for underwater digital communication (NATO, 2017). Optical or electromagnetic communication is used to link autonomous platforms and to support nodes at high data rates and very short ranges (Lloret et al., 2012). Speeds of up to 30 Mb/s have been demonstrated over distances of several meters (Al-Halafi and Shihada, 2018). Optical links have an energy efficiency of 30 kB/Joule compared to ∼100 bits/Joule for acoustic communication, so they can also be more power efficient for high data transfer rates.

Autonomous platforms use active acoustic sensors for acoustic communications and direct observations. Particularly in shallow water, the acoustic channel changes rapidly due to bathymetry, changing boundary interfaces, and physical oceanographic conditions. The limitations of computational techniques to robustly track the rapidly fluctuating shallow water acoustic channel also impact oceanic observation applications. Physical layer challenges to shallow water channel estimation lead to cross-layer issues that pose important design constraints to observation technologies that rely on efficient communication between acoustic sensors. Different strategies are needed based on how the ocean state affects the physical layer channel (Stojanovic, 2007). For example, a network of AUVs using acoustic sensors will need to continuously update the inter-sensor data transmission rate as the channel capacity between any two sensors changes due to changing multipath and other forms of acoustic scatter.

In the last decade, several solutions have been proposed (Akyildiz et al., 2005; Chitre et al., 2008; Singer et al., 2009) to solve the channel estimation challenges to underwater acoustic communications: compressive sampling, rateless coding techniques, and cooperative transmission techniques. Compressive sampling (Candes et al., 2006; Donoho et al., 2006; Baraniuk, 2007) and a diverse suite of mixed non-optimization techniques (Sen Gupta and Preisig, 2012; Ansari et al., 2016, 2017; Zhou et al., 2017a,b; Jiang et al., 2018; Wu et al., 2018) have been recently applied to follow the shallow water acoustic channel. Rateless coding techniques (Brown et al., 2006; Castura et al., 2006; Chitre and Motani, 2007) address the issue of uncertainty in channel state information, and therefore provide efficient, robust communication between a transmitter and a receiver. Cooperative transmission techniques increase wireless network capacity (Han et al., 2008; Vajapeyam et al., 2008; Wang et al., 2011; Cheng et al., 2012) through multiuser cooperation in the physical layer.

Platform Coordination

At the highest level, programs such as the ARGO float system (Schmid et al., 2007; Roemmich et al., 2019) coordinate autonomous platforms in the sense of maintaining distributed coverage of observations. Gliders (Paley et al., 2008; Testor et al., 2010, 2019) have been more directly coordinated in regional and local process studies. The architecture for a truly integrated global glider network is a work in progress. Early discussions (Bellingham, 2006) of adaptive sampling considered the interpretability of irregular observations as a key factor.

Outstanding sampling capabilities are possible when different AUVs are deployed in large numbers (Testor et al., 2018). Depending on the studied phenomena, different strategies can be adopted using different AUVs. There could be some that are dedicated to high-resolution measurements and others dedicated to providing information at larger spatial and temporal scales to assess the oceanic background. Methods are also being developed to allow autonomous systems to coordinate observations in challenging environments. Long-range acoustic signaling has been demonstrated as an AUV navigation method which can enhance multi-platform missions in GPS-denied environments such as under Arctic ice (Freitag et al., 2015; Lee et al., 2017).

Design exercises are used to decide the optimal numbers of different platforms to be deployed, considering a given scientific objective. Ocean numerical modeling can simulate the sampling of the platforms in relatively realistic virtual oceans. The optimization challenge is to meet the scientific objectives at the lowest possible cost. These design studies are now an important part of oceanography and will become more important in the future.

Both civilian and military researchers are considering the design of interoperable AUVs (Carrera et al., 2016; Constanzi et al., 2018; Phillips et al., 2018). Current work is focused on increasing the autonomy of AUVs and Autonomous Surface Vehicles (ASVs) and developing standards for interoperability between heterogeneous platforms to decrease the requirement for complex specialized platforms.[19]

Several institutions are making progress toward integrated systems of heterogeneous platforms focusing on persistence

[18] https://www.energy.gov/sites/prod/files/2017/04/f34/administration-wec-prize.pdf

[19] http://www.swarms.eu/

in the maritime environment[20] (Braga et al., 2017; Schmidt Ocean Institute, 2018). Many experiments have demonstrated heterogenous networks of autonomous platforms working together (Schofield et al., 2010; Huet and Mastroddi, 2016; Centurioni et al., 2017; Lindstrom et al., 2017; Marques et al., 2018; Phillips et al., 2018; Testor et al., 2018). Military trials, as depicted in **Figure 5**, also demonstrated interoperable communications using a standard protocol for underwater digital acoustic communications (LePage et al., 2015), and adaptation of sensors and systems based on real-time environmental conditions (LePage, 2018). Recent trials have demonstrated decentralized, dynamic task assignment (Ferri et al., 2018).

FUTURE VISION

Existing autonomous observation systems have shown that there are many complex levels of dynamics in the ocean from global to meso and local, each coupled in non-linear ways. To meet the need for a better, more integrated Ocean Observing System, we need advances at the sensor, platform, and system levels, including data interoperability. Compact, low-power sensors that are calibrated and stable, will enable more and better observations for more EOVs. Robust strategies for cross-calibration of sensors will enable reliable quantitative interpretation of data from large numbers of autonomous sensors. We need autonomous platforms that are more affordable, more modular, more capable, and easier to operate. *In situ* power generation will also extend endurance for some types of autonomous platforms, including standardized docking stations that will also enable AUV communications and recharging. Standardized communications for autonomous platforms will improve ease of use and enable coordinated behaviors. Improved autonomy and communications together will enable self-guided adaptive networks of AUVs to increase effectiveness further.

Improvements in autonomy will have three aspects: hardware, control, and operations. As sensors and platforms have more capability and energy capacity, more measurements become possible. Control systems and software will have more sophisticated states and reactions to sensor inputs, which both allows the platform to handle a wider variety of circumstances without direct operator control, and allows the operator to better know the state of the autonomous platform with less communication bandwidth. Operational autonomy is increased by reducing operating costs.

The future technical vision includes expansion of current capabilities [such as more bio-geo-chemical (BGC) Argo[21] profilers or adopting routine plankton monitoring on GO-SHIP[22] lines], significant technical updates to existing systems (such as advanced batteries in gliders), and paradigm shifts from new capabilities (such as sensor breakthroughs to enable widespread adoption autonomous platforms).

There are several factors that are common to all of these. One factor is the need to deal with large quantities of data. Eventually, all these data will need to be processed efficiently. For applications such as human health warnings, tsunamis forecasts

[20] https://www.cmre.nato.int/news-room/news-room/847-cmre-successfully-demonstrates-systems-for-persistent-autonomous-and-real-time-maritime-surveillance

[21] http://www.argo.ucsd.edu/

[22] http://www.go-ship.org/

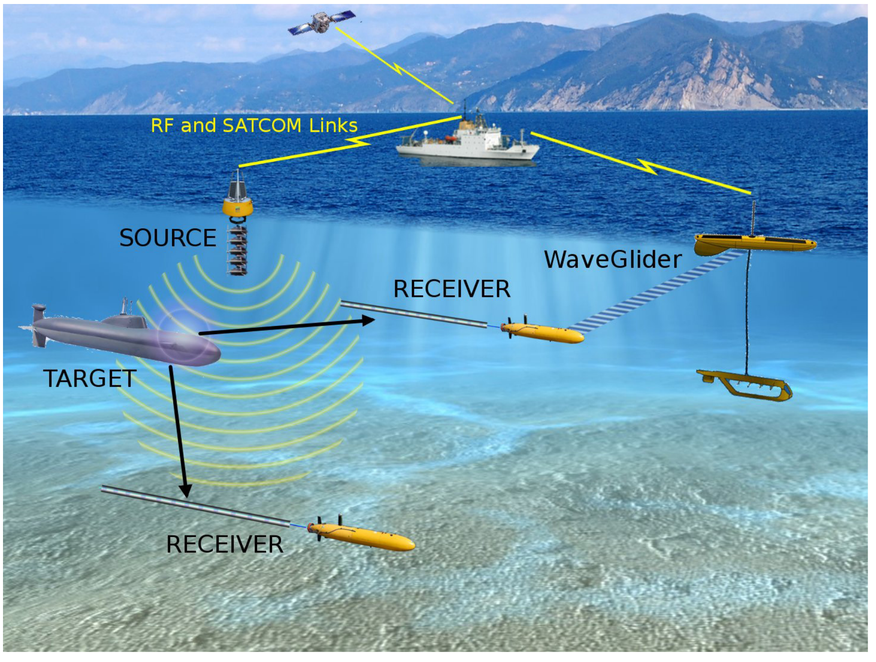

FIGURE 5 | A conceptual description of a cooperative network of AUVs.

and weather modeling, the data have the most value when they are available in near real time. Large datasets need an integrated approach to communication and then processes for translation of data to knowledge, which supports societal impactful decisions by end users (Buck et al., 2019). From the user perspective, another important factor is trust of data and information. For this, traditional factors of quality assurance / quality control (QA/QC) and provenance need to be adapted to future needs, accommodating greater automation and machine to machine paradigms (USIOOS, 2017). A third factor is documenting and making available the methods used in observations and analyses across the value chain of data to information in order to support reproducibility and interoperability. This encompasses both standards and best practices (Pearlman et al., 2019).

Sensors

The ideal sensor for future autonomous platforms will be cost-effective, compact, interoperable, web-enabled, and self-identifying. Cost-effective sensors may be suitable for large-scale production, and could leverage features of modern electronics, such as communication, positioning, and miniaturization. Compact sensors are autonomous multifunctional integrated packages. Web-enabled sensors acquire, pre-process, store, and transmit data in standardized formats. Interoperable sensors integrate with existing observing systems. Self-identifying sensors can communicate metadata through protocols such as PUCK[23] and may also support real-time QA/QC. These ideal features will be implemented differently in different types of sensors. The following discussion focuses on sensors for selected biological applications as a specific example.

Some future multi-purpose sensors will function in air and water (Moline and Benoit-Bird, 2016). Multi-purpose features could be for calibration, as is currently done with oxygen optodes (Bittig et al., 2015), or for improving functionality, such as using a single camera to achieve 3-D obstacle detection and avoidance (Shah and Johnson, 2009).

Integrated sensor networks are needed for detecting macro-pollution, microplastics, and oil spills, ultimately leading to better response and mitigation through timelier interdiction. The trend toward small analysis instruments, such as gas chromatographs and mass spectrometers, allows *in situ* processing to send digital data rather than water samples back to the laboratory. Deploying high-resolution optical nitrate sensors around water catchment areas provides critical information on agricultural and farming runoff. These data are critical for assessing the impact of croplands on areas such as the Great Barrier Reef.

A variety of spectrometers described in Section 0, such as fluorescence sensors, are already used for ocean measurements. More broadly integrating such sampling sensors into autonomous platforms enables more efficient and effective data collection. Sample selection will preferably be driven by AI and adaptive sampling methodologies through closely coupled sensors and autonomous platforms.

There is a need to go "beyond fluorescence" and beyond bulk optical properties. It is important to make observations that can characterize how carbon, nutrients, and energy are partitioned across diverse forms of life. The ideal sensor is a "lab on a chip"[24] which can readily interface with autonomous platforms (Beaton et al., 2012; Grand et al., 2017). In addition, for optical sensors, there are opportunities to leverage consumer technologies to provide a foundation for a new generation of chemical and biological observations. These could provide improved measurements of productivity and biomass in the world's oceans. In addition, more comprehensive monitoring of biological diversity is needed (Muller-Karger et al., 2018) for determining how food webs sustain ecosystem services, such as fisheries, carbon storage or release, and sediment formation. This involves not only optical systems, but acoustic observations. Optical sensors, especially the flow cytometers and imaging devices, are still very expensive. Inexpensive optical sensors are needed for more widespread use, possibly leveraging mobile phone camera and solid-state laser technology. Imaging devices also generate large quantities of data and images that require automated expert classification, data curation, archival, and distribution.

Sensor fusion is the integration of data from multiple sensors. An interesting challenge is automating the merging data from sensors that observe different views of a phenomena, such as ocean color satellite observations and *in situ* biology monitors (Boss et al., 2018), where the geo-spatial dimensions are different. Coarse ($>$10–30 m resolution) space-based data and point measurements can be linked through modeling. With the advent of advanced computing and access to cloud resources, models should improve so that the contributions of moderate resolution imaging and point data can be more effectively integrated. Another challenge is the fusion of biological observations, e.g. 'omics' and plankton sampling. Even simply the merging of multi-level 'omics' would be a step forward, deriving from the techniques developed in medical research (Huang et al., 2017).

Passive acoustic monitoring will see continued improvements in data handling, detection, classification and localization, and standardized metrics. Terminology (ISO, 2017) and soundscape metric standards (Ainslie et al., 2017) need wider adoption, as well as best practice methodologies. Analyses will more often be computed onboard to identify sounds of interest, react to events, and communicate results in near-real-time. Acoustic data loggers will have wider bandwidth and longer endurance. Sensor fusion will increase. An example of homogeneous fusion is using hydrophone arrays to determine the direction of detected events. An example of heterogeneous fusion is combining mammal vocalization detection on gliders with AIS tracks to evaluate risks of ship strikes in traffic lanes. Balancing the use of the ocean with the impacts of anthropogenic sound requires improved fidelity of species- and population-based monitoring and better understanding of soundscapes.

Platforms

As costs decrease, and science capabilities and reliability increase, the growing number of autonomous platforms at sea will

[23]http://www.opengeospatial.org/standards/puck

[24]https://noc.ac.uk/technology/technology-development/instruments-sensors

complement and extend observations that were conventionally done with manned platforms.

Autonomous platforms with greater control autonomy will begin to replace the typical pre-programmed missions of today. Advances in signal and image processing have allowed onboard learning and classifiers. Larger storage and enough processing power allow more on-board decision-making, which enables more control autonomy. Autonomous platforms will execute more complex survey missions, using measurement results to directly plan subsequent measurements. The question of how far this capability can be foreseen. Can an autonomous system be used to launch Argo floats? Going further, can there be an automated fleet of factory ships which can build and release sensors/platforms as needed to sustain a global observing system (Marlon Lewis, personal communication, Sept 25 2019)? To what extent can fault tolerant systems be designed so the learning curve to mature operational platforms can be shortened?

Not going too far into the future, advanced vehicles will have intelligent decision-making capabilities in navigation, energy management, and error handling (Vedachalam et al., 2018). Vehicles will plan their path based on model predictions to accomplish a goal. ASVs will replace manned vessels in supporting short-range acoustic positioning systems for AUVs, and longer-range acoustic navigation systems will begin to see regular use. Long-endurance autonomous systems that have enough energy to use inertial navigation may improve accuracy using new data inputs such as observed seafloor bathymetry (Salavasidis et al., 2019), under ice networks and communications with surface platforms. Platforms will also be more tolerant of failures. Early fault detection will trigger behaviors to mitigate equipment or data loss.

In addition to platform design and operational cost reductions, improvements in sensors will reduce costs by reducing science payload power requirements and enable the use of progressively smaller platforms. Many unmanned vehicles are already semi-modular with the ability to add sections for more payload. In the future, some of them may also be multi-domain (ONR, 2018; Weisler et al., 2018) and auto-reconfigurable, depending on the task autonomously selected or manually assigned.

Long-term deployments of more energy-intensive vehicles will become more commonplace as vehicle charging and wireless data transfer capabilities are added to remote infrastructure, such as Cabled Observatories (Manalang and Delaney, 2016) and marine hydrokinetic energy system installations (LiVecchi et al., 2019). Temporary docking installations may be used in areas of intensive monitoring, such as deep well decommissioning.

Light intervention AUVs (I-AUV) are hovering vehicles with manipulator arms that can focus on a single object or small area for an extended period. As I-AUVs become available they could complement ROVs in some applications (Ridao et al., 2015). Advances in docking I-AUVs will extend the mission profiles (Cruz et al., 2017).

There are visions of a paradigm shift in platform capabilities. Work is underway to develop a system that can self-deploy, and perform the aerial, surface, and subsurface functions of a drone, an ASV, and an AUV. Several vehicles that achieve flight and underwater missions are in the research phase (Edwards, 2017). The Monterey Bay Aquarium Research Institute (MBARI), working with the Office of Naval Research (ONR), is developing an entirely new vehicle that uses ground effect in flight mode to reduce energy requirements and extend persistence. After transiting in flight mode, the vehicle then lands on the water surface to await instructions, perform an action, then take off again. It can act as a relay between other similar systems, or it can submerge and function as an AUV. The concept is to imitate sea-going birds. Birds, such as pelicans, use ground effect for low-energy transit, then land or dive underwater. This new hybrid system has been dubbed Shearwater[25] (**Figure 6**). MBARI is currently building a functional scale model to demonstrate the capabilities (ONR, 2018). The goal of such an innovative design is to greatly increase operational autonomy.

Energy Sources

Developments in batteries for terrestrial vehicles will be leveraged in the short term to increase vehicle endurance. Docking and recharging stations will also extend mission duration[26] (Maguer et al., 2018) but will require primary energy sources, such as shore cables, liquid fuels, or *in situ* harvesting.

Presently, power sources include batteries, cabling, or generation of solar, wind or diesel power on buoys at the surface. Due to their high energy density, hydrocarbon fuels will undoubtedly continue to be part of the solution for recharge stations. Going forward, *in situ*, and particularly sub-surface energy harvesting, are likely to be increasingly able to meet energy demands for underwater instrumentation and AUV charging. By providing renewable power without surface expression, marine energy technologies (i.e., wave, current, and thermal gradient conversion) could enable multi-year persistence that enable wholly new frontiers in science, security, and economic development (Copping et al., 2018). Due to the intermittency of renewables, energy storage will be needed at sea to provide consistent and rapid recharge or power supplies (LiVecchi et al., 2019).

Routinely incorporating sub-surface marine energy conversion systems into autonomous platforms will require further technology development guided by collaboration with end-users. For example, while the resource intensity of wave energy is orders of magnitude larger than other *in situ* resources and theoretical conversion efficiencies are high, practical conversion efficiencies are relatively low and survivability in extreme events must be improved. Progress is being made in these areas and gains in autonomy and reliability achieved in ocean observing will also broadly benefit future energy harvesting technologies. Finally, standards for docking stations will also be required for platform interoperability that can facilitate broad adoption by the ocean observing community.

[25]http://bts.fer.hr/session/shearwater-the-future-of-hybrid-autonomous-marine-vehicles/

[26]https://www.ecnmag.com/blog/2018/05/navys-underwater-wireless-charging-station-can-improve-remote-uuv-mission-performance

FIGURE 6 | The Shearwater vehicle concept under development (Image courtesy MBARI 2012©).

Communication

Satellite communications systems being developed will soon be available with more bandwidth per user, fully reconfigurable coverage footprints, dynamic routing of uplink and downlink, and dynamic bandwidth allocation (Fenech et al., 2015). Satellite communication costs are expected to decline with the increasing use of nanosatellites.[27] Though the market is for rural areas and developing countries, coverage over the ocean will support more data transfer for autonomous operations. Higher communication bandwidth will enable platforms to support new sensors as well as operate more independently from shore or support vessels, increasing both hardware and operational autonomy.

Many future applications will still use acoustic communications as it is the only practical long-range method to support increasing needs for navigation, control, and dynamic mission planning based on subsea observations. Positioning and navigation will be improved by increased use of communication between platforms, particularly in deep water. More use of inter-platform communication will also allow more navigation-capable vehicles to support less expensive, less capable vehicles. This increases operational autonomy by maximizing the submerged endurance of platforms for under-ice operations, deep ocean mapping, and for other geo-referenced observations.

The bandwidth and ranges for acoustic communication will not improve dramatically, even if more complex protocols and strategies are used (Melodia et al., 2013). The current pioneer for an international standard underwater digital communication is JANUS-STANAG 4748 (NATO, 2017). Wider adoption of standards for communication will improve interoperability and ease of use for autonomous platforms.

A solution to bandwidth limitations in underwater communications is to use drifting, temporary surface buoys as low-power repeaters that connect to a subsurface platform using an acoustic modem. The surface buoy could communicate using conventional radio or satellite methods. These devices will need to be self-configuring and easily deployed, and would be most useful in specific applications with relatively large numbers of autonomous platforms in a given area. This type of repeater network would enable multi-vehicle operations, widely dispersed sensor networks and remote operations on-shore command and control when needed. This is conceptually similar to animal tracking networks where low power marine animal borne sensors couple to receivers distributed in the tracking area (Heupel et al., 2018).

Underwater life has evolved sophisticated acoustics-based communications suited to their environmental conditions. Animal communication systems are a source of inspiration for new technology, and also a consideration in developing methods that do not conflict with or disrupt natural communications (Li et al., 2017; Barbeau et al., 2018; Sherlock et al., 2018).

Optical communications will become more popular for short range, high bandwidth inter-vehicle communication. Real-time control of untethered vehicles during complex subsea manipulations may be possible using optical links to transfer high bandwidth video and vehicle/dock attitude parameters (Farr et al., 2006; Domingo, 2008). Improved optical links will allow autonomous vehicles to download larger data sets to docking stations or relay nodes that connect with surface and land-based platforms. Docking station standards and best practices are needed to allow heterogeneous platforms to use shared nodes for communications and power.

Platform Coordination

Confidence in autonomy will increase as data- and model-driven control strategies become robust; however, more integrated mission planning is needed to realize the full potential of heterogeneous networks of autonomous platforms (Ludvigsen et al., 2016). Navigation will integrate environmental forecasting and tactical prediction. Advanced platforms will be able to build their situation awareness. Some systems may even use additional models to update their mission objectives and improve the usefulness of their observations.

There have been many discussions about platform coordination for monitoring EOVs (Testor et al., 2019), marine fauna (Verfuss et al., 2019), etc. Each type of application optimizes platforms and sensors to the needed observations. Yet it is the ability to use collected data for multiple end purposes that should be taken into consideration (acknowledging the cost impacts of added requirements). These types of trades should be done in a systematic way, done from the perspective of an integrated architecture for global ocean observing. This is consistent with the GOOS vision of "a truly integrated global ocean observing system that delivers the essential information needed for our sustainable development, safety, wellbeing and prosperity" (Tanhua et al., 2019). The architecture should be layered so that there is both a top down and bottom up flexibility.

[27] https://www.bbc.com/news/business-43090226

This will allow effective integration of existing networks and encourage expansion of observations through innovation and technology advances. For example, the effectiveness of teams of platforms will increase as systems become better able to sense, interpret, and act upon unforeseen changes in the environment and vehicle. Vehicles navigating in a formation will require exchange of navigational information and some guidance for coordinating observations.

Sensors and platforms need new standards and agreed processes for data exchange and shared data interpretation. Standards will improve network flexibility and create broadly interoperable systems. For example, navigation techniques for under-ice or deep ocean positioning could be applied in other domains to reduce the need for surfacing, simplify mission profiles and increase measurement efficiency. Flexible and interoperable networked systems can be simpler, more modular, and produced in higher volumes to decrease per-unit capital and operational costs. More cost-effective platforms can be deployed in larger teams to make observations more quickly and over larger areas. Applications could include upwellings in boundary currents or underwater eruptions where temporal dynamics may be of interest.

Widespread use of teams of autonomous platforms may require improved awareness of regulations (Huet and Mastroddi, 2016; Chiang and Tapia, 2018). Depending on the size and nature of the autonomous platform, users may need a better understanding of collision regulations, insurance requirements, and liability. Technology developments that could help include mandatory onboard black boxes and water-spatial management tools, such as public databases to register autonomous platform operations.

Downstream Connectivity

The value of data is in the information that can be created from it to impact societal applications. Connecting sensors and platforms with data repositories and end-users is a priority. The Sensor Web Enablement (SWE) suite of OGC includes standards for sensor/platform interfaces, encoding data and metadata, and data transmission (Buck et al., 2019). Semantic interoperability is achieved using marine-relevant vocabularies to enable the unambiguous description of metadata and data (Buttigieg et al., 2016). The European NeXOS Project demonstrated these capabilities (Río et al., 2018). The next steps are the evolution of SWE to address linked open-data services and the introduction of the Internet of Things (IoT) in ocean observations. These capabilities are being drawn from developments outside the ocean community. Additional features, such as access control, security models, and interface of SWE with the web standards, need to be addressed as ocean observation systems evolve to adopt SWE and IoT (Buck et al., 2019).

Future autonomous platforms will generate large data sets covering basic oceanographic to complex acoustic or even eDNA data. The community should adopt principles of Findability, Accessibility, Interoperability, and Reusability (FAIR, Wilkinson et al., 2016). FAIR principles and increasing real time availability will make data usable by new communities and reduce the overhead in integration between observing networks. For example, improved biogeochemical numerical ocean models are developing and will become a significant new user of oceanographic observations collected by autonomous platforms such as biogeochemical Argo (Fennel et al., 2019). The application of the FAIR principles in combination with new tools such as digital notebooks (e.g., Jupyter) will enable more complete documentation of data analysis and thus a revival of reproducible research facilitating trust in scientific results.[28]

RECOMMENDATIONS

Thirty years ago, Hank Stommel laid out a vision of autonomous vehicles as small, cheap, torpedo-like drones that would glide around in the ocean on their own, with an ingenious new engine that would draw power from the ocean itself. While the details are different, the vision is not too far from the reality today. The next decade of vehicles, sensors and systems will be able to examine the ocean in new ways and discover yet more that may is unimagined.

(1) Autonomous platforms should decrease in cost and increase in reliability. True autonomy will be achieved within a decade based on trends in automobiles, mobile phones and advanced processors. Ocean systems can also benefit from advances in reliability engineering for these high-volume, mass-production products.
Recommendation: there is a cultural change that is needed. Platforms are low volume, relatively high cost. The ocean community should come together to agree on applications where observations need order-of-magnitude increases, then agree on a limited number of platform specifications and a price limit for a volume buy of each.

(2) Improved interoperability of sensors, platforms, and their interfaces will reduce costs.
Recommendation: new standards and best practices are needed. Current standards and best practices should be made broadly discoverable and accessible, and new standards and best practices should be created/adapted for ocean observing. Standards, such as the IoT and SWE, should be drawn from non-marine communities for use in ocean observing systems.

(3) Teams of platforms, each with improved autonomy, can transform operational patterns and capabilities. There are many applications where networks of multiple vehicles can improve operational efficiencies, such as seabed mapping, ecological monitoring, oil spill monitoring, and oil platform decommissioning.
Recommendation: develop operational architectures at global and regional scales to provide a backbone for active autonomous networking of platforms.
Recommendation: docking station standards should evolve to allow heterogeneous platforms to use shared nodes for communications and power. A standard organization such as IEEE Standards Association should be engaged to move this forward.

[28]https://github.com/Reproducible-Science-Curriculum

(4) The power and energy limitations will become less severe with battery improvements and lower power sensors, but batteries will be insufficient for some applications. *In situ* energy harvesting has the potential to provide the necessary power.
Recommendation: energy harvesting technologies should be integral to the system design, for sensors, platforms, vehicles, and docking stations. Stronger connections are needed between the marine energy and ocean observing communities to coordinate among funding sources, researchers, and end users.
(5) As the population of AUVs increases, it will be necessary to consider regulations for operating autonomous platforms, particularly in coastal areas.
Recommendation: regional teams should work with global organizations such as IOC/GOOS in governance development. International networks such as EGO for the emerging glider operations should also provide a forum for addressing governance.
(6) Automation is being brought forth by various economic sectors and ocean autonomous vehicles will leverage this through technology transition. There are also opportunity for new system concepts which can advance the current autonomous system paradigms.
Recommendation: while maturing current systems, support new and creative concepts, such as the Shearwater hybrid vehicle, through government grant funding and mature these so transition to industry and larger scale production is possible.

AUTHOR CONTRIBUTIONS

CW led the integration of the manuscript. JP contributed significantly to the overall structure, introduction, sensors, future vision, and recommendations. BF, LG, WK, MA, ED, SH, AMag, PT, SSa, and SSi contributed to AUVs and other platforms. AG and HS contributed to acoustic communications. AMar, FC, and WK contributed to sensors. FM-K, RV, and VN contributed to *in situ* optical sensors. JP, PT, and SK contributed to data, standards and best practices. BP, HS, and AC contributed to marine renewable energy. SM, AMar, HS, and CW contributed to passive acoustics. All authors contributed to the article and approved the submitted version.

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