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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.

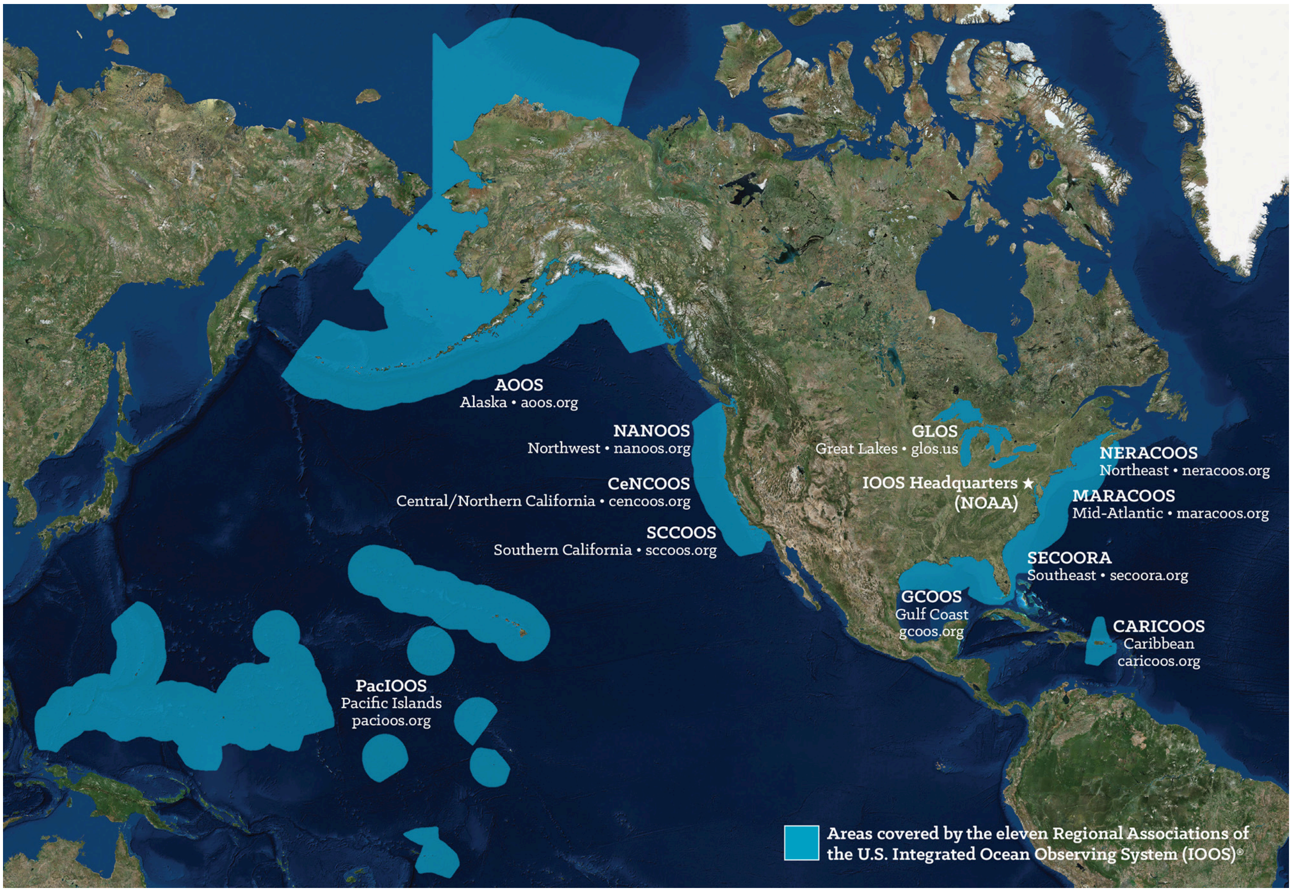

FIGURE 1 | Map of IOOS regional associations.

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

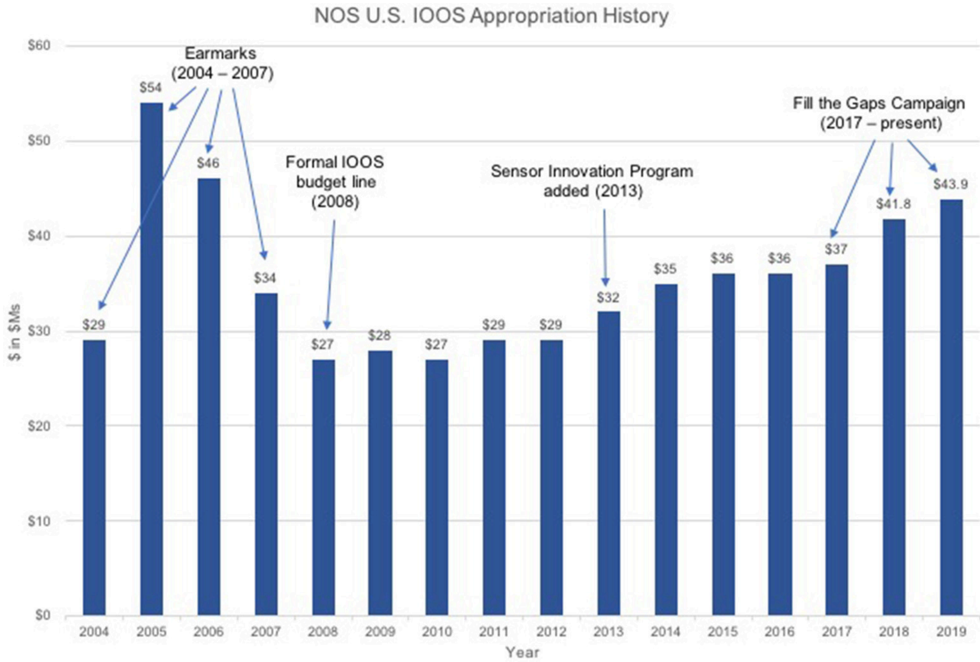

FIGURE 2 | IOOS Funding History.

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. 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

[5]https://sensors.ioos.us/

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/

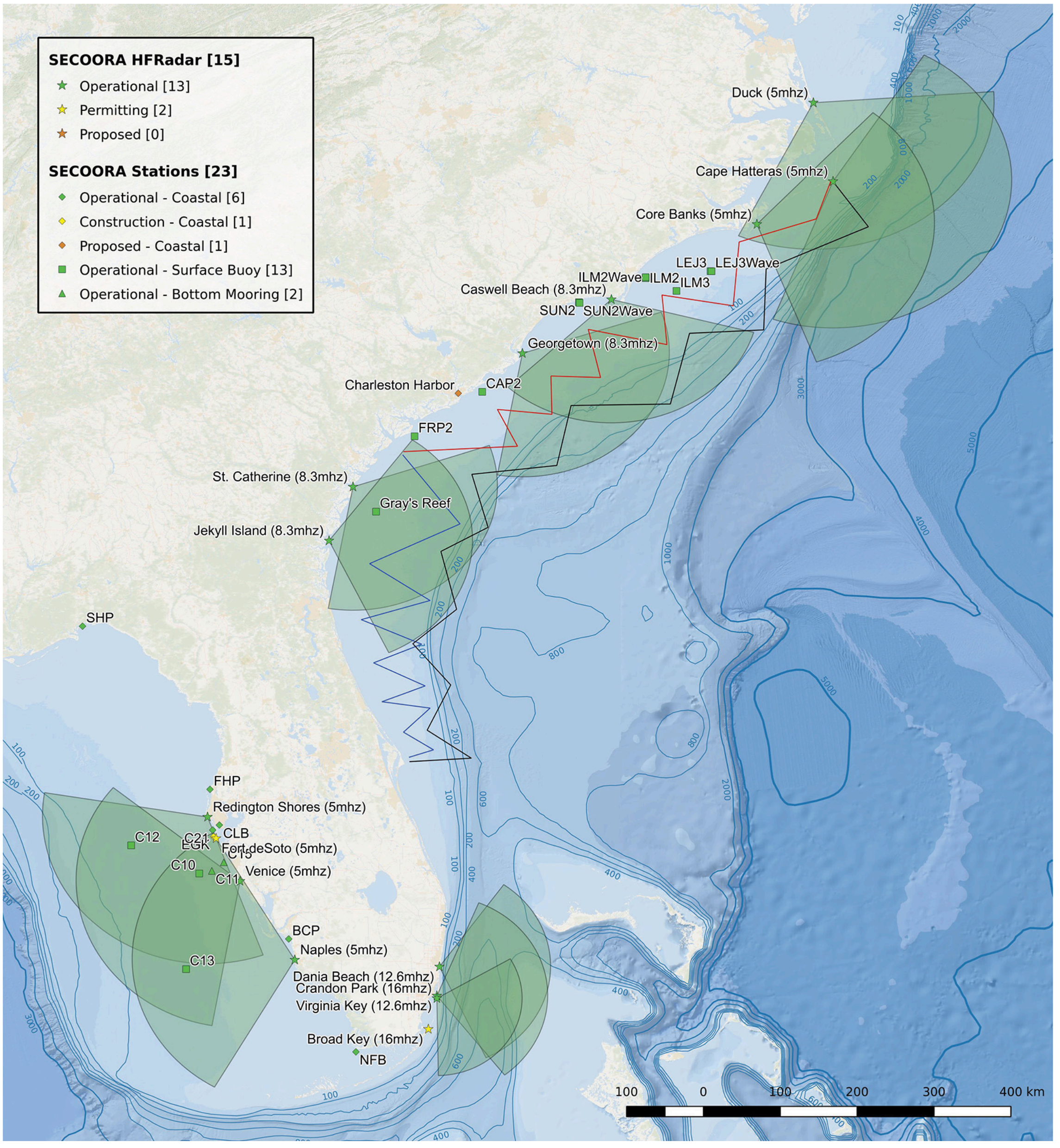

FIGURE 3 | The SECOORA geographic domain and observing infrastructure.

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,

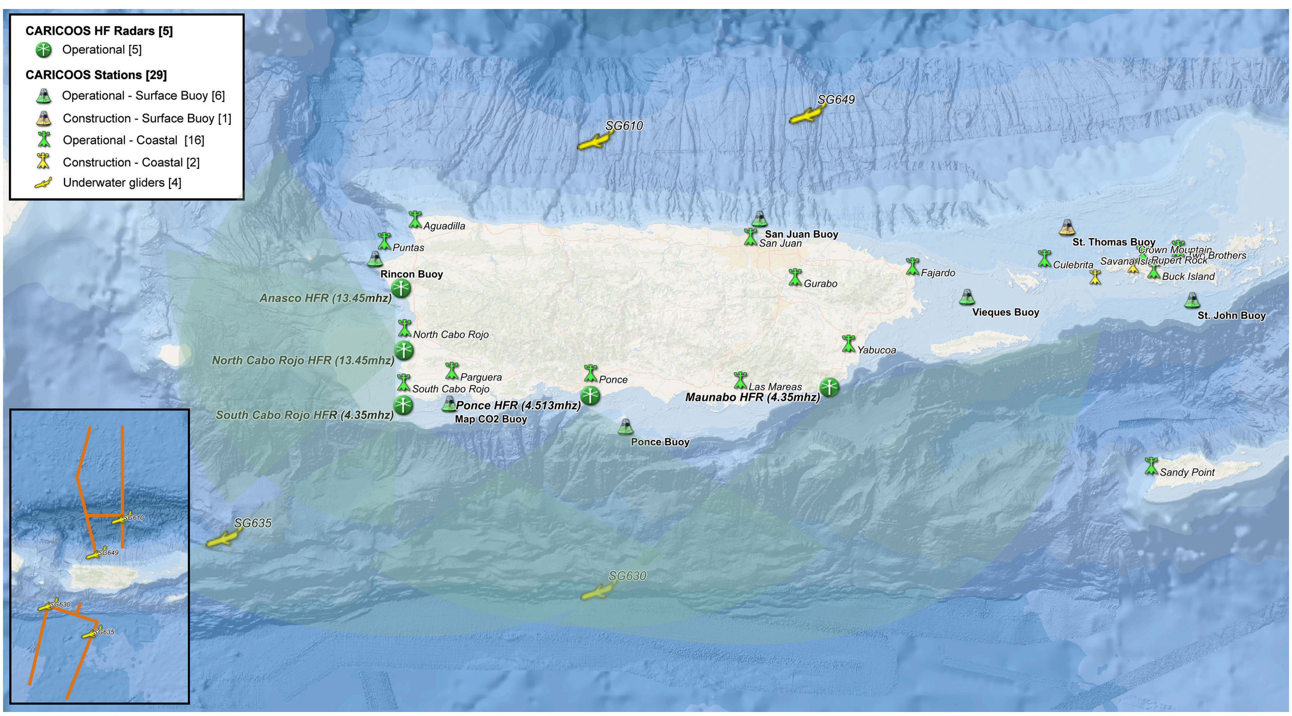

FIGURE 4 | The (CARICOOS) geographic domain and observing infrastructure.

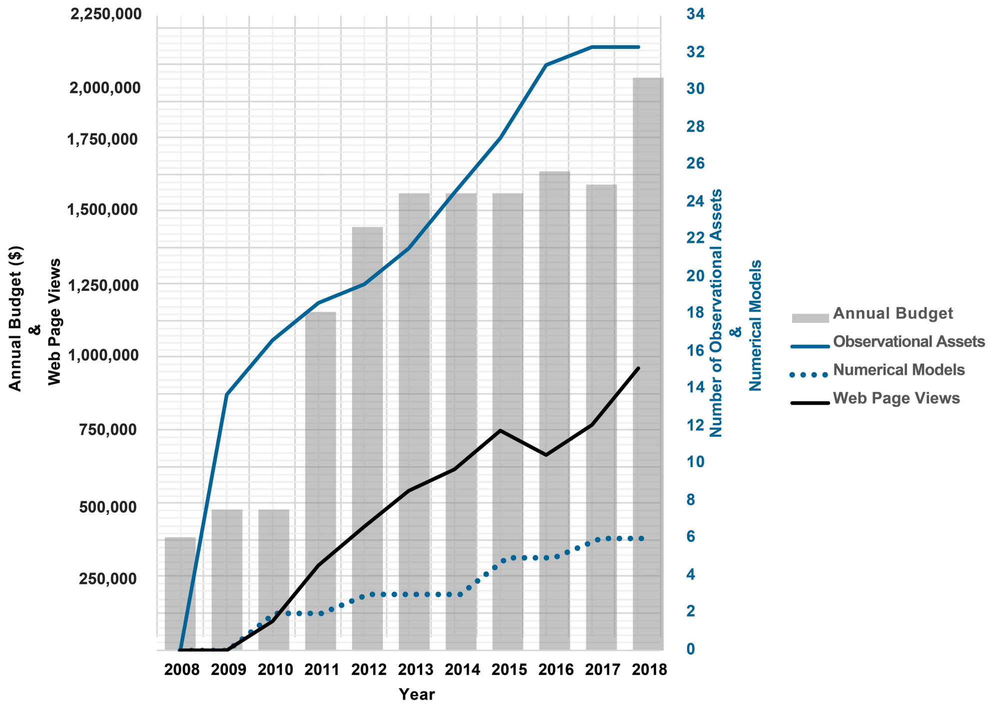

FIGURE 5 | CARICOOS website use compared to annual budget.

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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