MEASURING THE PERFORMANCE OF OCEAN OBSERVING SYSTEMS

PILOT METRICS FOR SEA LEVEL RISE, OCEAN ACIDIFICATION, AND HARMFUL ALGAL BLOOMS

IOOC
Interagency Ocean Observation Committee

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EXECUTIVE SUMMARY

Effective management of the ocean requires the ability to track, predict, manage, and adapt to changes in the marine environment, all of which are made possible through ocean observing. Across the ocean at any given moment, vast and varied ocean observing platforms are gathering data; ships, buoys, floats and drifters, autonomous and remote vehicles, tagged marine animals, aircraft and satellites, and coastal radars record immense amounts of physical, chemical, and biological data. When compiled and synthesized, the data from these ocean observing platforms are essential to understanding weather and climate, maritime operations, natural hazards, national security threats, public health, and living resources. They also aid in responding to challenges like sea level rise, extreme weather, and other ocean conditions that significantly impact economies, ecosystems, and society.

Sustained, integrated ocean observing systems have been evolving rapidly over the last century; over the last several years this growth has accelerated due to major innovations in data processing methods, machine learning (i.e. artificial intelligence), technology miniaturization, cloud computing, and other technological advancements. These new capabilities have created robust global and regional ocean observing networks. Measuring and assessing the performance and value of these networks is increasingly critical for characterizing the state and progress of the ocean observing system, maximizing and optimizing the efficiency of the system, guiding future ocean observing programs, prioritizing asset placement, and tracking the wealth of impacts observation-based ocean knowledge has on meeting societal needs.

Deriving metrics for ocean observing systems can take an extensive number of different forms, considering the range of themes, categories, and criteria that comprise the ocean science and technology enterprise. Consequently, the United States Interagency Ocean Observation Committee (IOOC) commissioned an expert group, the Metrics for Ocean Observing Systems Task Team (MOOS-TT), to assess metrics based on readiness, feasibility, and the inherent value to the target audience of U.S. federal agencies, policymakers, and the general public. The resulting framework was applied to selected thematic areas with fairly mature observing systems: sea level rise, ocean acidification, and harmful algal blooms. This was done to constrain the metrics to a few manageable pilot studies. The resulting pilot metrics cover a range of activities, from observing infrastructure and assets to economic impacts, in an effort to assess the baseline of, measure progress in, and identify gaps in the selected observing systems. Their development highlights the challenges (e.g., development, resourcing, coordination) and potential value (e.g., economic impacts, management decisions) of implementing a more robust U.S. Integrated Ocean Observing System (IOOS). Recommendations on next steps towards achieving such a System are noted in the concluding section. The MOOS-TT notes that evaluations of the value of such a System against the associated cost of generating metrics should be addressed in any follow-on activity.

Summary of recommended next steps:

- The IOOS enterprise, either through the Program Office, IOOC committee members, contractors, or some combination thereof should invest in collecting high-quality, repeatable metrics
- IOOC Task Team should collect the same pilot metrics again, to measure how easily they can be replicated
- Additional thematic topics should be investigated or reviewed to determine level of maturity for expanding beyond the pilot metric topics
- IOOC must also assess the:
  - Process and resources required for agency contributions
  - Ways to assess the impact of metrics on the target audience

BACKGROUND AND METHODS

BACKGROUND

Metrics are tools for supporting actions that allow programs to evolve toward successful outcomes, promote continuous improvement, and enable strategic decision making. Additionally, they are now utilized as a means of communicating the goals, status, and progress of large-scale ocean observing programs, such as the Joint Technical Commission for Oceanography and Marine Meteorology *in situ* Observations Programme Support Centre (JCOMMOPS) and Ocean Networks Canada (ONC). The purpose for developing a set of ocean observing metrics for U.S. IOOS is to:

- Characterize the scope and nature of IOOS observations
- Gauge progress toward achieving established ocean observing goals
- Identify gaps in observations

These metrics are intended to help monitor and evaluate the status of U.S. observing activities at-large, which can then be used to assess the entire IOOS and determine the health of the System, and how adjustments to smaller component programs can improve the System. These metrics should reflect indicators related to essential ocean variables (EOVs) — physical, chemical, or biological — to help understand how well elements of the ocean domain are observed in time and space, determine vulnerabilities and opportunities in observing systems, and inform management and policy decisions to promote oceanographic research and operations. Detailed metrics relating to the management of individual observing networks are not the aim of this effort and are left to agency programs to develop and utilize.

From a technical perspective, ocean observers often use a metrics framework in the management of collecting and evaluating oceanographic measurements from specific platforms, such as data quality assurance, best practices in deployments, and more. However, metrics at a broad scale are relatively undefined, and so have been made the focus of this report. The primary objectives for this effort are:

- Identifying the audience for IOOS metrics;
- Developing a suite of measurable and repeatable metrics;
- Recommending a process for agencies to contribute towards those metrics;
- Assessing future pilot metric development projects;
- Suggesting ways to assess the impact of metrics on the target audience; and
- Providing next steps towards moving beyond pilot metrics.

The pilot metrics will aim to integrate across various system components, characterize the status and overall progress of the system development over time, determine and track the performance of observing activities, and ultimately measure impacts on socioeconomic indicators. Such observing metrics can generate information applicable to wide-ranging audiences, including lay, managerial, and subject matter experts. For example, measuring the overall progress of ocean acidification observations could be very useful to program managers and policymakers as they strive to understand the strengths and weaknesses of the networks and guide future priority activities. Linking metrics on the progress of observing systems to metrics on the impacts of those systems will generate public and political intelligence on the inherent value of long-term programs that measure carbon uptake in the ocean and their benefits to people and the planet. In other words, metrics that characterize status and progress along the value chain, from observing to impact, would generate incredible short- and long-term value to the ocean observing enterprise.

AUDIENCE

The team identified five audience categories for these metrics: Policymakers, U.S. federal agency managers, scientists/researchers, operational experts, and the general public. The "type" of audience comes from standard nomenclature used in journalism and technical communication developed by Colorado State University *(https://writing.colostate.edu/guides/page.cfm?pageid=328&guideid=19)*, which determines how the metrics might be used for particular groups. The three types of audiences are: 1.) "lay" who are most likely unfamiliar with ocean observing and connect with the societal impacts, require more explanation and visual aids; 2.) "managerial" who require the metrics for decision making and need only the facts or statistics; and 3.) "experts" who demand technical and specialized information. The table below lists potential specific audiences within each category and the primary (1°) audience type – acknowledging that multiple audiences can exist within each entity (table 1). The ocean observing metrics identified in this exercise yielded information relevant to managerial and expert audiences principally. The authors attempted to identify and provide ocean observing metrics applicable to lay audiences in this report; however, more research is needed for translating technical ocean observing information to lay audiences.

Table 1. Potential audiences of metric findings by category.

AUDIENCE	TYPE (1°)
Policymakers	
G-7: Multinational	Managerial
International Organizations: IOC, IOCCP, IOCCG, etc.	Managerial
Legislative Branch:US Government and State Level	Lay
Executive Branch – OMB, NSTC, OSTP, CEQ, CENR	Managerial
Executive Branch – USGCRP, NOC, IARPC, National Science Board	Lay
US Federal Agencies	
Program Managers	Managerial
Interagency Ocean Observation Committee	Managerial
Scientists/Researchers	
NGO's, Federal, State, Academia, Industry	Experts
Managerial/Operational	
NGO's, Federal, State, Academia, Industry	Managerial
Public	
Informational, Citizen Scientists	Lay

METHODS

Three major ocean themes were selected around which to set up the pilot metrics: sea level rise (SLR), ocean acidification (OA), and harmful algal blooms (HABs). Within each theme, the MOOS-TT developed metrics that met the following criteria: impactful, easy to track over time, and highlight progress and/or gaps in the science. Metrics were selected based on the feasibility of acquiring the information and the anticipated impact of the resulting data. Additionally, the resulting metrics are designed to represent the capabilities of most federal agencies that collect ocean observations with the IOOS regional partners.

Metrics were collected in coordination with many of the federal agencies involved in ocean observing, primarily the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the Bureau of Ocean Energy Management (BOEM), the Environmental Protection Agency (EPA), the United States Geological Survey (USGS), the National Science Foundation (NSF), and the IOOS Regional Associations. Some of the metric data was collected from federal or interagency databases or websites. Other metrics were developed from federal agency reports or by directly posing questions to agency scientists. In some cases, metric data was collected through the creation of survey materials that were circulated among agencies/groups for population.

THEME: SEA LEVEL RISE

Sea level is rising globally due to the melting of land glaciers and thermal expansion of water (Church and White, 2011). Sea level rise is also a contributing factor to more frequent flooding events. These events can be a threat to coastal communities and have several negative impacts, including habitat destruction, damage to infrastructure and property, and weakening of local economies. Sea level rise is measured by several different observing systems. One is with tide gauges that measure the daily changes in tides. Over a long period of time, there is a trend that can show how much the total sea level is changing at that tide gauge. Global measurements are done by using tide gauges around the world and averaging their change. Altimeter satellites were launched 25 years ago to help measure sea level from a global perspective. Since tide gauges can only be installed where land exists, there are large portions of the ocean that were not monitored. According to Aviso+ "Altimetry is a technique for measuring height. Satellite altimetry measures the time taken by a radar pulse to travel from the satellite antenna to the surface and back to the satellite receiver. Combined with precise satellite location data, altimetry measurements yield sea-surface heights." Monitoring the changes in sea level rise through observations can help to predict, mitigate and adapt to the changing sea level.

METRIC: Percentage of GLOSS tide gauges co-located with GPS or GNSS capabilities

Sea Level change does not just happen in the United States, but globally. In order to monitor this change, there is a global set of almost 300 tide gauge stations (300 is the goal, currently there are only 291 in the array) that make up the Global Sea Level Observing System (GLOSS) network and provide the optimal sampling of the global ocean. Over 100 countries contribute to this network. In 2012, this network agreed that having co-location of Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) capabilities at tide gauges would give a better accuracy of the change at that location. The definition of co-location used for this metric is having a tide gauge and GPS/GNSS antenna (or benchmark), less than 10 km away and tying the two stations together routinely with the tide gauge calibrated to an accuracy better than 1mm/year (preferably at annual intervals but up to an interval of 3 years). Currently there are 219 out of 291 (75%) GLOSS core tide gauges that report their co-located GPS/GNSS data to the GLOSS data center (SONEL).

Figure 1. GLOSS core tide gauges in the SONEL network.

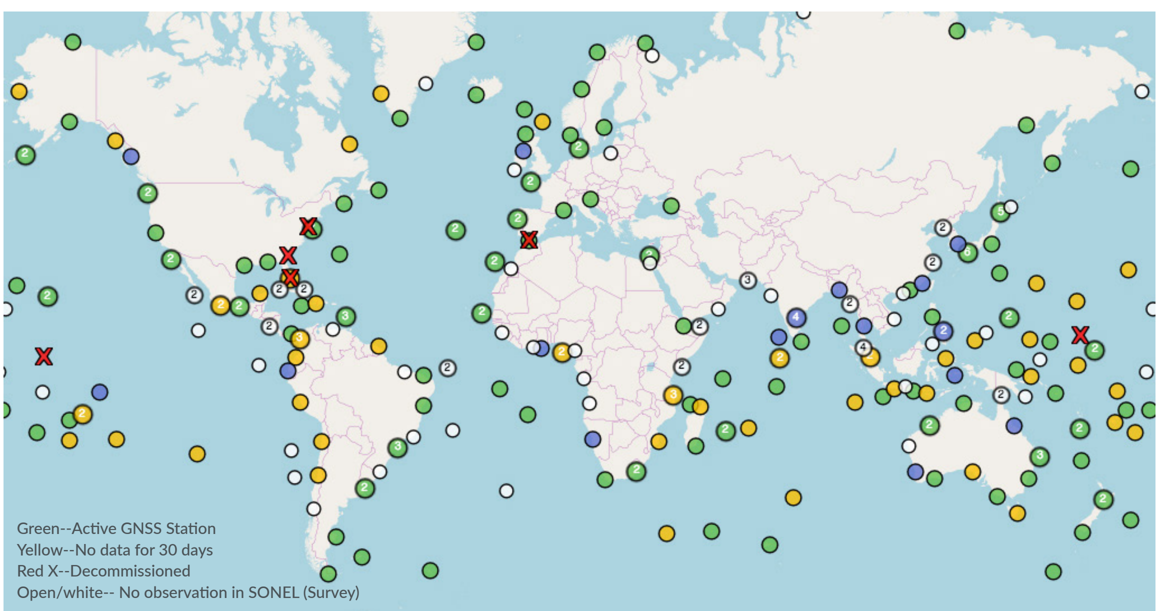
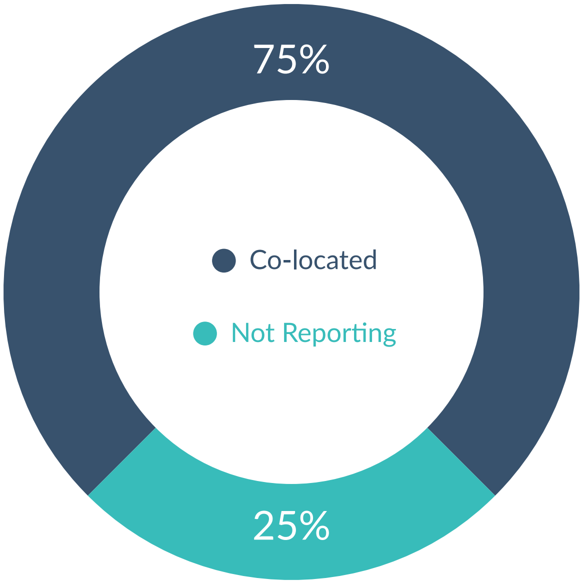


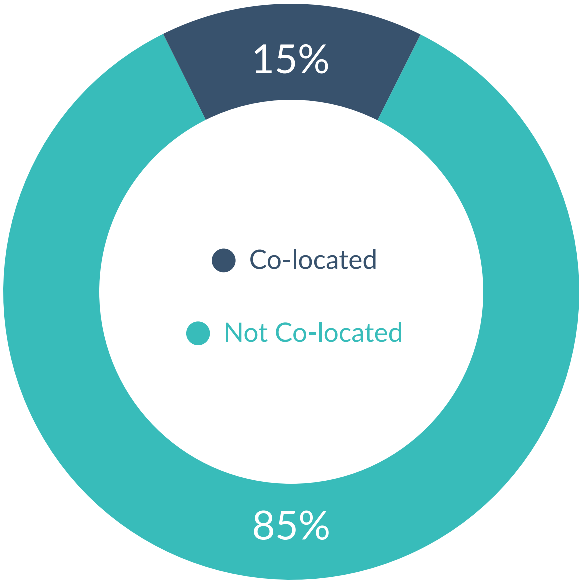
Figure 2. GLOSS tide gauges with co-located GPS or GNSS capabilities.



METRIC: Percentage of U.S. tide gauges with ties to co-located GPS or GNSS capabilities

Using the same standard as the global tide gauges to define co-located capabilities, the U.S. has lagged behind the global percentage. Only 31 out of the 210 stations (15%) are currently co-located. The U.S. is also working to make this data accessible through SONEL (currently not available and not able for researchers to access).

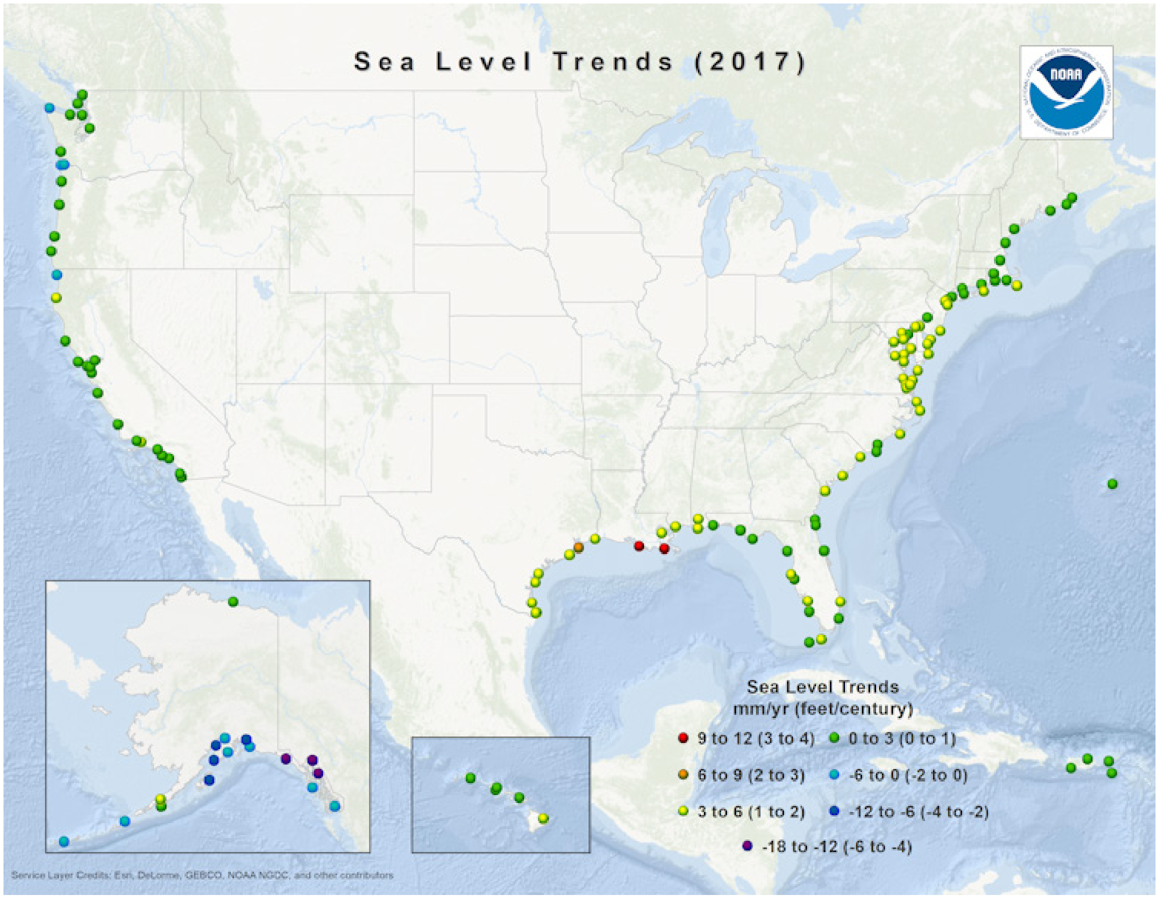
Figure 3. U.S. tide gauges with co-located GPS or GNSS capabilities.



METRIC: Number of U.S. tide gauges reporting real time (within 24hrs)

Real-time data from tide gauges allows for immediate detection of sea level changes. This can show short-term changes as well as long-term ones. For the short term, these changes can show important information about tsunamis. In the U.S., NOAA operates 210 tide gauges. All of these gauges have real time data accessible.

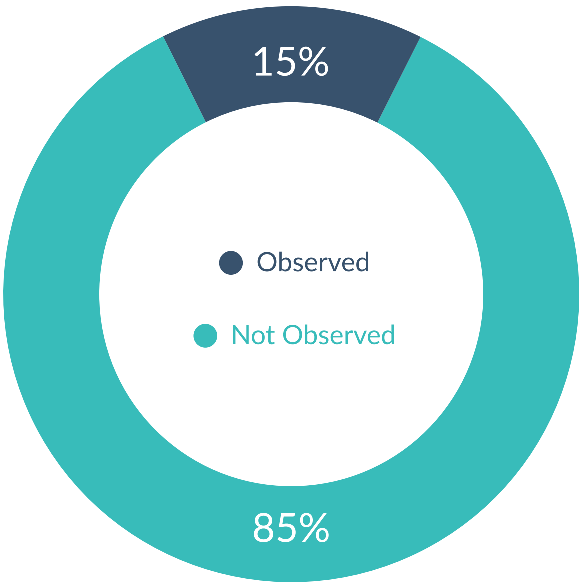
Figure 4. NOAA 2017 Sea Level Trends.



Satellite altimetry METRIC: Percentage of 0.5 degree ice-free regions covered every 10 days by satellite altimetry measurement

Satellites are another way that we monitor what is happening globally. However, there are not many satellites specifically dedicated to monitor changes in ocean height. When the globe is broken into segments using half degree (lat/long) boxes, then a percentage of how much of the Earth is observed by these satellites can be calculated. These are still very large boxes, approximately the size of Rhode Island. This large area will be reduced as new satellites are launched. With this method, currently only 15% of the ice-free global ocean is observed every 10 days.

Figure 5. Percentage of 0.5 ice-free regions covered every 10 days by satellite altimetry measurement.



= Land; = Sea Ice; = Altimeter coverage; = Open ocean/no altimeter coverage

Figure 6. Satellite coverage plot at .25 degrees for 10 days in 2015 (January 11-20th). Contributing satellites were Jason-2, Cryosat-2, and AltiKa/SARAL.

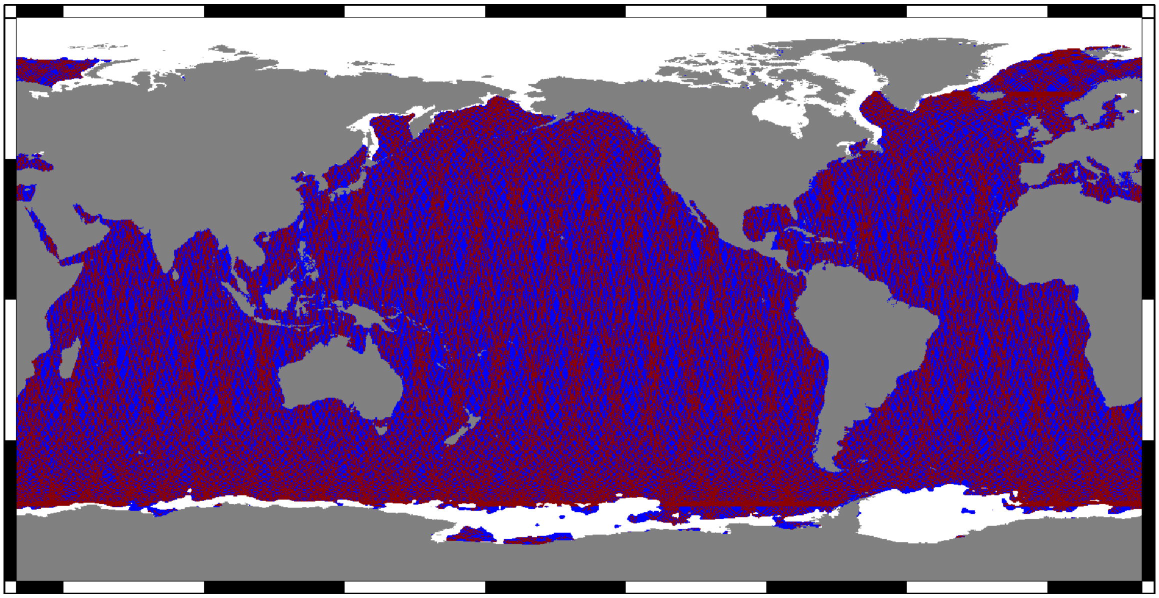
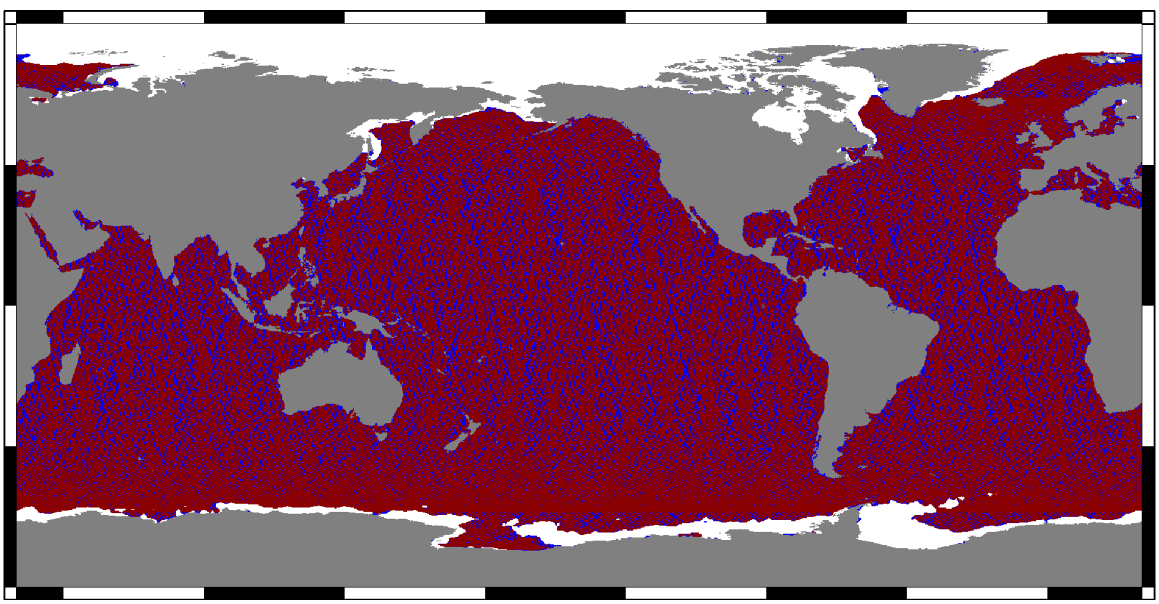


Figure 7. Satellite coverage plot at .25 degrees for 10 days in 2019 (January 11-20th). Contributing satellites included Jason-3, Sentinel-3A, and Sentinel-3B, in addition to Jason-2, Cryosat-2, and AltiKa/SARAL.



THEME: OCEAN ACIDIFICATION

Ocean acidification (OA) refers to the decreasing pH and carbonate ion concentrations of ocean waters, due primarily to the uptake of carbon dioxide (CO_2) from the atmosphere. (e.g. Feely et al., 2004, 2009; Orr et al., 2005). Over the last 250 years, as atmospheric CO_2 emissions from the combustion of fossil fuels and other human activities have increased, ocean surface waters have become 30% more acidic, due to the absorption of the increased atmospheric CO_2 (Feely et al., 2009; Gruber et al., 2019). OA has profound impacts on the ocean and organisms that inhabit it, as it reduces the capacity of many calcifying organisms to produce and maintain their shells or skeletons, which are made of calcium carbonate (Busch et al., 2014; Riebesell et al., 2016). These organisms range from pteropods to shellfish to corals, all of which contribute to global job and food security. Ocean observations of key physical, chemical, and biological parameters are critical to understanding and predicting how the oceans will respond to increasing OA. Documenting these changes can alert stakeholders and industry partners of corrosive (e.g., acidic) events which can impact coastal communities and economies.

The United States has invested significantly in observing OA. Figure 8 represents an initial inventory of U.S.-owned OA assets. The inventory was collected through the Global Ocean Acidification Observing Network (GOA-ON) Data Portal, which includes a non-comprehensive list of assets operated by NOAA, the NSF Ocean Observatories Initiative (OOI), and several academic institutions. Representatives from NOAA and BOEM also supplemented the inventory information with assets not listed in GOA-ON.

A total of 101 assets were inventoried in this pilot round, which had the aim of capturing U.S. investments in ocean acidification observations. A subset of these data was used to develop pilot metrics, as described below. Understanding the quality and quantity of OA assets/measurements that the United States has is critical to being able to monitor the health of the observing system. A healthy observing system can track changes of water properties that are of importance to stakeholders and provide forewarning of imminent changes that could result in catastrophic economic losses.

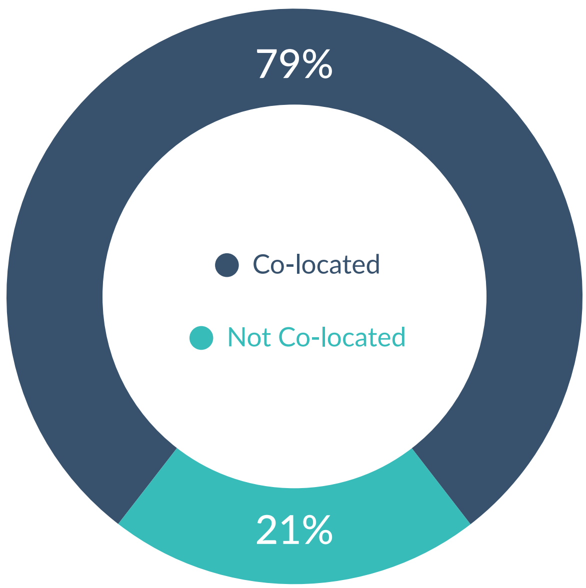
Figure 8. Map of U.S.-Operated/Maintained OA Assets

METRIC: Number of co-located complementary observing sensors that include some or all of: dissolved oxygen, optical parameters, turbidity, or nitrate.

For OA, co-location of sensors refers to having an additional sensor in the water (e.g., dissolved oxygen; turbidity; nitrate; and optical parameters such as chlorophyll or chromorphic dissolved organic matter (CDOM) fluorescence, and particle backscattering), on the same platform as that where OA measurements are being collected. Having co-located sensors augments the power of OA measurements by providing additional environmental information to contextualize measurements. Co-locating sensors can, in addition, help improve the ability to quality-control sensor data and provide information on other variables that are important to, for example, water quality. Similar to the "number of observing days" metric, this metric serves as a baseline indicator of the number of assets that are in the water. Ideally, the complementary observations should either expand — adding co-located instruments to existing OA moorings or adding OA sensors to other moorings with additional sensors would be signs of a "healthier" system — or remain the same. A contraction or reduction of the number of co-located sensors would indicate a decline in the observing system, which would have a negative impact on environmental monitoring. Much like the previous metrics, analyzing the trend from year to year is the most important factor.

Of the 101 assets inventoried, 80 (79%) of the assets contained an additional sensor and are therefore considered to be co-located.

Figure 9. Co-located assets out of 101 total assets.



METRIC: Number of observing days during which surface moorings measure the full dynamic range of the ocean acidification system

This metric will serve as a baseline indicator, with changes in this metric indicative of the health of the observing system that is able to track OA. In coastal zones, where conditions are highly variable through space and time, it is important to capture sufficient frequency of sampling, i.e., enough measurements to resolve the complete diurnal cycle of OA in a 2-hour period at a given location. The ultimate goal of this metric is to build a comprehensive list of all OA assets measuring the full dynamic range of the system, complete with data from all relevant government agencies. This metric will track the extent of U.S. surface moorings measuring OA in coastal regions through space and time. The most important factor is the trend from year to year, to assess growth or contraction of the system through time.

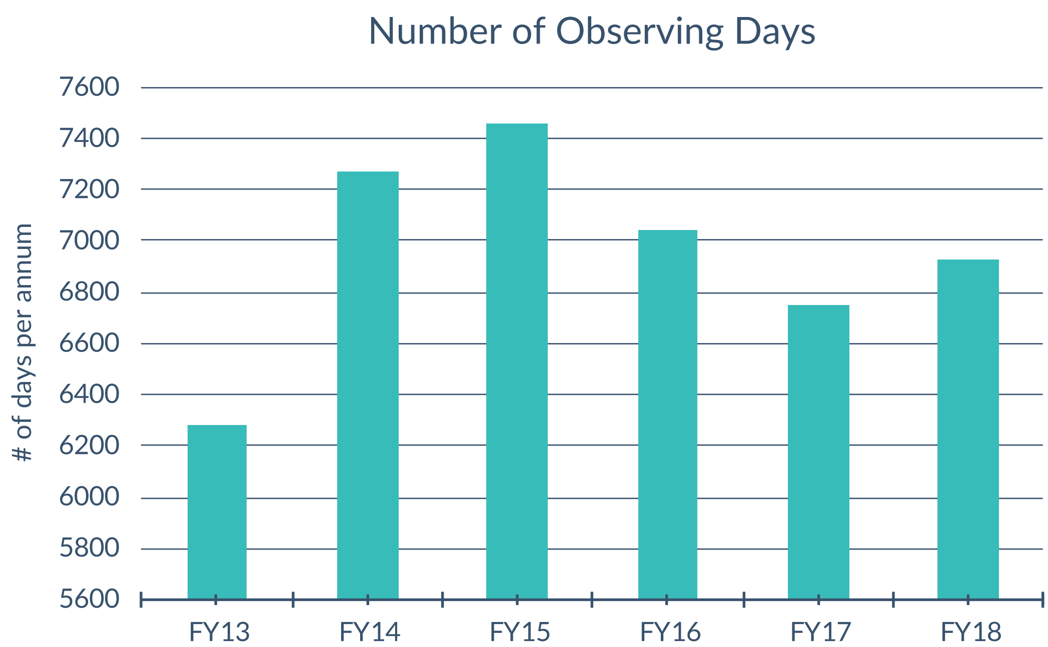
For this metric we consider surface moorings that include a suite of sensors which describe the daily cycle of ocean carbonate chemistry. This is needed in order to measure and track long-term changes in ocean chemistry in response to OA. Sensors which measure temperature, salinity, and partial pressure of carbon dioxide (pCO2) are necessary to accurately estimate ocean acidification; these sensors must be located on the same platform. Each day, every mooring should provide data for the determination of a complete daily cycle with a fully functioning sensor suite (a minimum of 8 observations per 24 hours). Thus, a single mooring deployed for a full year should achieve a maximum number of observing days of 365. An observing day only counts if all three sensors (temperature, salinity, and pCO2) measure and report data eight times in a 24-hour period. This is a measurement of the footprint of the system, and this number of observing days increases as more moorings are deployed (i.e., as coverage of the network is extended). In the first year of deployment, this number may be less if deployed mid-way through the year.

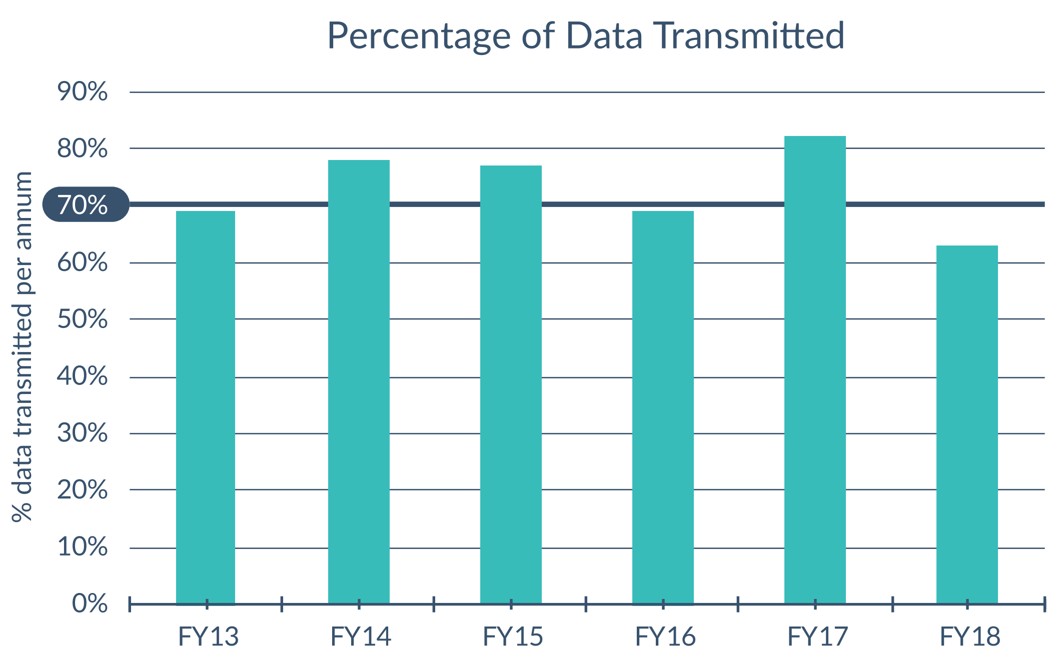
In some regions, the maximum number of observing days for a given asset may be less because of environmental conditions, such as ice coverage. If the asset is taken offline and not replaced, the number of observing days will decrease; such a decrease may indicate that there may be issues with the observing system network.

METRIC: Delivery of data from surface moorings (70% target)

It is important that the data being collected by surface moorings are transmitted from the observing platform to the scientists. This indicator is an efficiency metric and is calculated as the number of actual observing days divided by maximum observing days possible for a given mooring (see above and Figure 10). An actual observing day occurs when an observing asset successfully transmits a minimum of eight observations obtained from each of the three sensors (temperature, salinity, and pCO2) each day. Ideally, the number of actual days should equate to the maximum number of observing days such that the derived indicator is 100%. However, provided that each GOA-ON asset demands annual servicing and maintenance, it is expected that no GOA-ON asset will successfully report 100% of the time. Rather, depending on the asset, it may be taken off-line for a period of days to weeks if there is a problem or to complete servicing and maintenance. As a result, we define 70% network-wide as a suitable objective for the network. As a result of unforeseen events such as sensor failure or extreme weather events which demand off-lining an asset, it is possible that the indicator may not achieve 70% in a given year, but in general, this is the intended target. Consistent low delivery of data may indicate a systemic problem in the network. The first graph of Figure 10 shows that the overall footprint based on number of observing days has been relatively stable over time. The second panel shows that, while the overall trend has been fairly stable at or above the 70% target, in fiscal year 2018 (FY18), there was a drop in the data availability, suggesting that there may have been a problem with part of the network that warrants closer attention.

Figure 10. The prototype measures for the number of observing days and percentage of data transmitted; these measures are an indicator of the health of the OA observing system, based on data collected by NOAA. These measures will be broadened to include other agency data.





METRIC: Number of national OA assessments that document the state of OA

Tracking OA on a national level over time allows the scientific community and the public to understand how OA may affect ocean ecosystems and the communities that depend on them around the United States. National assessments utilize scientific data produced by observing assets and put it in a context that is useful for decision makers. This metric, specifically the number of reports on OA that are produced at a national level, provides information on the rate of data usage for decision making and public awareness products (bottom up), as well as on the need of such reports by decision makers (top down). A hiatus or increase in the number of reports produced can be indicative, for example, of changes in policies and/or data availability (former), or a greater need for such information, respectively. There have been seven total national-level reports documenting the current state and likely trends of OA, among other ocean-related issues, since 2013.

2014 National Climate Assessment (NCA): The 2014 NCA, synthesized by the U.S. Global Change Research Program, summarized the impacts of climate change on the United States at the time of publishing and moving forward. Chapter 2, "Our Changing Climate," includes a "Key Message" section on increasingly acidic oceans as a result of rising atmospheric CO_2 levels. The section also highlights the detrimental effects of ocean acidification on calcifying animals.

2018 Fourth National Climate Assessment Volume II: Unlike the 2014 NCA, the 2018 report includes an entire chapter on the ocean and marine resources.

Second State of the Carbon Cycle Report (SOCCR2): In 2018, the SOCCR2 was released as a second installment of this decadal report. The SOCCR2 assesses carbon cycle science across North America and is a product of the U.S. Global Change Research Program. Chapter 17, "Biogeochemical Effects of Rising Atmospheric Carbon Dioxide," highlights the impact of OA on marine ecosystems.

National Science and Technology Council Interagency Working Group on Ocean Acidification, 2013-2016 (4 reports): In 2013, the Interagency Working Group on Ocean Acidification released the Second Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress on a Strategic Research Plan. The initial report was released in 2011. This series of reports was requested by the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act), which specifies that the working group will provide reports to Congress summarizing federally funded OA research and monitoring activities and describe updates regarding the strategic research plan. Reports were released annually from 2013 to 2016.

Figure 11. Seven National OA Reports Since 2013

THEME: HARMFUL ALGAL BLOOMS

Harmful algal blooms (HABs) occur when populations of some algae species grow, sometimes producing toxins that can have harmful effects on people, fish (including seafood), or other animals in the marine and Great Lakes environments. HAB occurrence, intensity, and duration has been increasing in recent years, costing an estimated $100 million in economic losses each year (Hoagland and Scatasta, 2006) and endangering public health and marine ecosystems. Nearly every coastal and Great Lake state is now impacted by HABs. Forecasting and providing warning of harmful algae blooms can prevent public consumption of toxic seafood, prevent inhalation of toxic air, prevent harm to fish and marine mammals, and help environmental managers respond effectively. Programs at the state, tribal, and federal level contribute to algal bloom forecasts and warnings that protect public health. These efforts also allow researchers to better understand the characteristics of specific HAB species and their potential impacts on coastal communities. Robust observing networks are essential to predicting and mitigating HABs.

The U.S. coastal and Great Lakes regions experience HABs differently based on the species that bloom in the region; the oceanographic and physical drivers of the bloom; the toxins they produce; and the impact they have on the ecosystem, people and economies. Monitoring programs must take into account these regional differences by adopting appropriate methods and technology. Monitoring is conducted by state and other agencies responsible for public health and safety, researchers and regional observing systems and, in some cases, by volunteers. In the lab, samples can be evaluated through microscopic enumeration, molecular probes and images that measure algal cell abundance, and antibody probes can test for the presence of toxins. Several regions use autonomous instruments, such as Environmental Sample Processors (ESPs), Imaging Flow Cytobots (IFCBs), and the Programmable Hyperspectral Seawater Scanner (PHYSS), which are deployed *in situ* to detect, identify, and measure harmful algal cells or toxins. Satellite images of coastal waters can also be used to identify HABs by measuring algal pigments in the water.

Sustained observations are needed to support forecasts and warning systems. Currently, most of the observations are supported by research grants, not by operational programs. Coastal regions with a sustained, operational observing system are better positioned to integrate monitoring assets from federal, state, and local programs; exchange data; and adapt to HAB threats as they arise.

METRIC: Regions with HAB observing network capabilities that contribute to forecasts

Several of the IOOS regions have observing capabilities that contribute to forecasting programs. IOOS regional observing systems collect observations and are developing and contributing to forecast models as well as data management, integration, and dissemination. In the Gulf of Mexico, NOAA's National Centers for Coastal and Ocean Science (NCCOS) in partnership with the Gulf of Mexico Coastal Ocean Observing System (GCOOS) contributes funding for HAB forecasts along the coasts of Florida and Texas, helping to predict and monitor *Karenia brevis* blooms that cause red tide. The Center for Operational Oceanographic Products and Services (CO-OPS) collects data from a variety of HAB monitoring partners in the region, analyzes the information to predict where a bloom might travel, and publishes a forecast bulletin weekly. In the Great Lakes, CO-OPS issues Lake Erie forecasts once or twice weekly during HAB season. The Great Lakes Observing System (GLOS) supports the data portal that provides streamline access to the multiple observations. The NCCOS is also funding support of pilot HAB forecasting systems in the Gulf of Maine and the Pacific Northwest. In California, the two IOOS Regional Associations, the Central and Northern California Coastal Ocean Observing System (CeNCOOS) and the Southern California Coastal Ocean Observing System (SCCOOS), support a HAB Monitoring and Alert Program (HABMAP) that collects data from shore station and the California-Harmful Algae Risk Mapping (C-HARM) forecast for predicting outbreaks of *Pseudo-nitzschia*, the diatom that produces domoic acid, which can cause large marine mammal mortality events. Additionally, the Alaska Ocean Observing System (AOOS) coordinates community sampling in remote rural areas that depend on shellfish from subsistence. The Caribbean Coastal Ocean Observing System (CariCOOS) displays the University of South Florida's Floating Algae Index on their website to alert people to large mats of *Sargassum* that can overwhelm beaches and waterways. In total, 10 of the 11 U.S. IOOS Regional Associations contribute to HAB forecasts and monitoring (Figure 12).

Figure 12. IOOS regions with HAB occurrences and observing capabilities contributing to forecasts.

To characterize the specific and diverse needs for HAB monitoring and forecasting, a regional approach is necessary. Each IOOS region, in conjunction with the appropriate state, federal, tribal, and other partners should identify high level goals for the next three to five years that can subsequently be used to track investments and their impacts at the national perspective. This report recommends tracking these reported regional priorities and what, if any, investments (resources, instruments, programs, etc.) are made to achieve these goals. These efforts are just getting underway as the need for operational observation systems to support operational forecasts is recognized, and more coordination is required to sustain these efforts. Similarly, NCCOS recommends establishment of a National HAB Operational Observing Network to ensure the sustained observations needed to support forecasts and warnings. Most of the observations are currently funded under research grants with no mechanism for sustained support.

METRIC: Economic impact of HABs

Harmful algal blooms are estimated to cost approximately $100 million dollars in economic losses per year (Hoagland and Scatasta, 2006), and quite possibly more given the ripple effects HABs can have on the many industries that rely on coastal waters. In 2015, an extended bloom of *Pseudo-nitzschia* (a marine diatom that produces domoic acid, a neurotoxin which is poisonous to shellfish and marine mammals) along the West Coast wreaked havoc on Dungeness crab fisheries, causing an estimated $97 million in commercial fishery losses and an additional $40 million impact to the region's tourism industry. HAB events negatively affect the fisheries and consumers that directly rely on seafood, but also often cause secondary damage to the businesses supported by these industries as well as coastal property values. The table below demonstrates several instances of significant economic damage as the result of a HAB event.

Table 2. Estimated economic damage from several recent HAB events.

Year	Region	Species	Economic Damage Estimate
2014	Toledo, Ohio	Cyanobacteria	$65 million in damage to tourism, recreation, property value, and water treatment
2015	Pacific Northwest	*Pseudo-nitzschia*	$97.5 million in lost Dungeness Crab Landing; $40 million in lost tourism spending
2018	Florida Coast	*Karenia brevis*	$20 million in tourism-related losses; Additional public health and fishing industry losses

To understand the value of sustained observations, this report recommends the development of a systematic approach to tracking the economic impact of HABs on communities, industry, tribes, states, and others, in addition to the monitoring of federal investment in HAB observation and forecasts. This will provide insight into how investments work to mitigate the impacts and increase the response to outbreaks. Demonstrating the value of observing investments may also be used as a tool for communicating to various stakeholders, including policymakers and resource managers.

SUMMARY OF FINDINGS

Individual ocean observing metrics, compiled and presented as a whole, paint a vivid picture of where the United States, and to a large extent, the world stands in its ability to measure ocean properties and change. The number of "things" in the ocean do not provide a meaningful metric, they must connect to the ability to measure something that has relevance to society. For instance, the pilot metrics for this study show that while the United States appears to have adequate tide gauges dispersed across the coastlines to measure sea level, the percentage of those co-located with GPS is very low (15%), handicapping the ability to accurately distinguish between shifting sea level versus shifting sea beds. Alternatively, observing assets providing ocean acidification data are meeting or exceeding the 70% efficiency metric annually, demonstrating that the current coverage of pCO2, pH, alkalinity, and dissolved inorganic carbon measurements can provide a baseline of chemical parameters and changes in the regions they are currently deployed. Establishing metrics for other variables of interest is more difficult, as in the case of Harmful Algal Blooms (HABs). The authors were only able to determine "regions" where HABs data is collected or to estimate the damage HABs cause, which highlights the need of more accurate observing capabilities. Overall, this report shows that metrics are essential for evaluating how well the United States monitors and predicts ocean properties and changes, and evidenced that these metrics require significantly more investment.

Establishing metrics across U.S. federal agencies and stakeholders is a challenging process that requires significant time and effort to initiate. This inherent difficulty prompted the task team to constrain the analysis to pilot metrics focused on three topics spanning the biological, physical and chemical sciences, and which have significant relevance to society: sea level rise, ocean acidification, and HABs. With the selected metrics topics, the team addressed the two core objectives of this exercise: identifying the audience for IOOS metrics and developing a suite of measurable and repeatable metrics. In total, the team identified five broad audience categories and nine pilot metrics across the three themes. The efficacy of metrics derived in this analysis varied considerably but provides a sound basis for addressing the remaining objectives: recommending a collection process; assessing future projects; targeting the audience; and providing next steps beyond pilot metrics.

METRICS

Identifying pilot ocean observation metrics for sea level rise, ocean acidification, and HABs produced a baseline for evaluating these topics and a potential model for broader data collection. Overall, the metrics demonstrate that observing capabilities vary across themes, and provide useful analysis of observing capabilities.

SEA LEVEL RISE

Changing sea level is primarily observed using tide gauges and satellites. For tide gauges, experts have determined that the accuracy is also dependent on the shifting sea floor on the Earth's crust due to a variety of factors which can be measured using GPS or GNSS. The baseline metric for measuring sea level are the 210 coastal tide gauges in the United States that report real-time (within 24 hours) and open data to the public. These tide gauges span the entire U.S. coastline, including Alaska, Hawaii, and the Great Lakes. Only 31 out of the 210 stations (15%) are currently co-located with GPS or GNSS capabilities. The United States is also working to make this data accessible through SONEL (currently not available for researchers to access). Looking at global sea level observing capabilities, there are 291 GLOSS stations and 219 out of the 291 (75%) are co-located with GPS or GNSS capabilities. Finally, satellite altimetry measurements provide the percentage of the world covered by oceans. Currently, 15% of the ice-free areas are observed every 10 days, which and will improve over time with planned satellite missions. In summary, the metrics show that while sea level measurements are sufficient for providing estimates, significant improvements are needed in co-locating U.S. tide gauges with GPS and GNSS, as well as feeding the data into global assembly centers.

OCEAN ACIDIFICATION

Observing ocean acidification requires the collection of several ocean variables (pCO2, pH, alkalinity, and dissolved inorganic carbon, as well as temperature and salinity) to provide an accurate depiction of changes. Successfully capturing OA measurements in coastal zones with dynamic conditions requires the ability to measure many or all of the referenced variables on one platform with a consistent frequency of sampling. The goal of these metrics is to (1) build a comprehensive list of all OA assets and the data provided from all relevant U.S. government agencies, (2) establish a baseline of the "health" of the system which can be tracked using the established metrics, and (3) document the state of OA publications on a national level. An inventory of U.S. surface moorings found that there are a total of 101 assets. Of these inventoried assets, the overall footprint of the OA observing as measured by number of observing days is fairly consistent, demonstrating consistent OA observing over time. The delivery of data from assets was on average around the target percentage (70%), but with years that were below the target. It is important to understand the reason for this variability and ensure that future data are normalized. In terms of co-located complementary observing sensors, 80 (79%) of the assets contained an additional sensor and are therefore considered to be co-located. There have been seven total national-level reports documenting the current state and likely trends of OA, among other ocean-related issues, since 2013.

HARMFUL ALGAL BLOOMS

Several of the IOOS regions have observing capabilities that contribute to forecasting programs. IOOS regional observing systems contribute by collecting observations; developing and contributing to forecast models; and managing, integrating, and disseminating data. Almost all of the 11 U.S. IOOS Regional Associations contribute to HAB forecasts and monitoring.

Harmful algal blooms are estimated to cost approximately $100 million dollars in economic losses per year, and quite possibly more given the ripple effects HABs can have on the many industries that rely on coastal waters. The metric also reported on three separate HAB incidents that totaled an estimated $222.5 million dollars in losses to the fisheries and tourism sectors.

LESSONS LEARNED

The metric research produced a wide variety of results — some metrics are easy to track and show clear opportunities for growth, while others revealed gaps in consistent measurements and information-sharing. Metrics that proved more difficult to collect share a number of common challenges, chiefly that federal agencies may monitor the same type of assets or systems, but the format or tracking methodologies often differ, making standardization and integration challenging. Resources and even definitions are not always consistent. For example, when collecting data on the number of sustained assets for a given measurement, the term "sustained" is defined differently depending on the source, making it difficult to identify contributing assets. Some of the metric data required a specific request of an agency scientist, versus those that can be found in centralized clearing houses of information, such as JCOMMOPS. This makes consistently monitoring the metric over a significant amount of time more burdensome and prone to inconsistencies in the way the metric is calculated. Finally, collecting national metrics may fail to capture the unique challenges and capabilities faced by different regions. With a theme such as HABs, observing needs can vary widely based on the characteristics of the coastal area and the algal species. In this case, metrics on HAB observing capabilities are better served by taking a regional approach as opposed to a national one.

NEXT STEPS AND ACTIONS

Developing pilot metrics is only the beginning of the process. Metrics must be used and evaluated over time to determine if they are meeting their intent and showing progress toward goals, and ultimately should inform decision-making processes. Moving beyond pilot metrics requires modifying the existing suite developed in this report and deriving metrics across other ocean observing themes. Proposed changes or metrics should take into account several factors:

1. Level of effort and funding required to find the data (weighed in relation to the predicted value of the metric).
2. Ability to identify an agency or program that will commit to regularly tracking the information.

Moreover, to maximize the potential value of metrics, each should be accompanied by a minimum set of documentation established by the metric developers. This will ensure data are collected with consistent methodology and at the established intervals. Additionally, best practices, including the recommendations listed below, should be standardized and each metric should be provided for review by the appropriate agencies on an annual basis:

- Metric ownership: While each pilot metric relies on support from multiple federal and nonfederal agencies, one federal agency should be named as lead for tracking, evaluating, and reporting on the measure to the IOOC and other groups as identified. All parties contributing to the outcome of each metric should be included in the details for transparency.
- Metric tracking: The metric lead should work with contributing parties to develop a process for tracking, to include shared resources to view progress toward the goal. The process should include a schedule for parties to provide information on progress (e.g., quarterly, semi-annually) to the lead agency. The lead agency should work with the IOOC to determine the best means for reporting progress to the committee.
- Metric evaluation and reporting: During the course of the first year, the lead agency should ask all contributing parties for information on if and how they are using the metric with their stakeholders. Identifying audiences for the metrics should be a component of the annual evaluation and factor into the success of the metric. Metrics should be evaluated regularly by contributing parties and users to evaluate the success of the measure, including recommendations for improvements or changes as needed. Outcomes and proposed changes from this evaluation should be reported to the IOOC at their discretion.

Program managers should consider how a metric contributes to ocean observing system design to inform the evolution of these metrics. While the complexities of the U.S. ocean observing system certainly make metric collection difficult, these same complexities point to the need for a systematic approach to evaluating our capabilities and ensuring investments are valuable to the ocean sciences community. Successful metrics can benefit program managers and researchers by defining how instruments and capabilities are working together and advancing our knowledge of the ocean.

DETERMINING FUTURE METRICS

The lessons learned in this pilot study are valuable in guiding selection of metrics and topics moving forward. Potential themes should be evaluated based on their feasibility, relevance, and ability to contribute to a more robust understanding of the U.S. ocean observing system. Authors selected the three topics in this study — sea level rise, ocean acidification, and harmful algal blooms — due to their perceived maturity and accessibility of data. Below is a strategic map of the Global Ocean Observing System (GOOS) elements (Figure 13, Table 3), which illustrates relationships to the core GOOS panels across major societal themes. This offers a list of 24 thematic topics, including the three addressed in this report.

Figure 13. GOOS Strategic Map, featuring potential topic areas for future metrics.

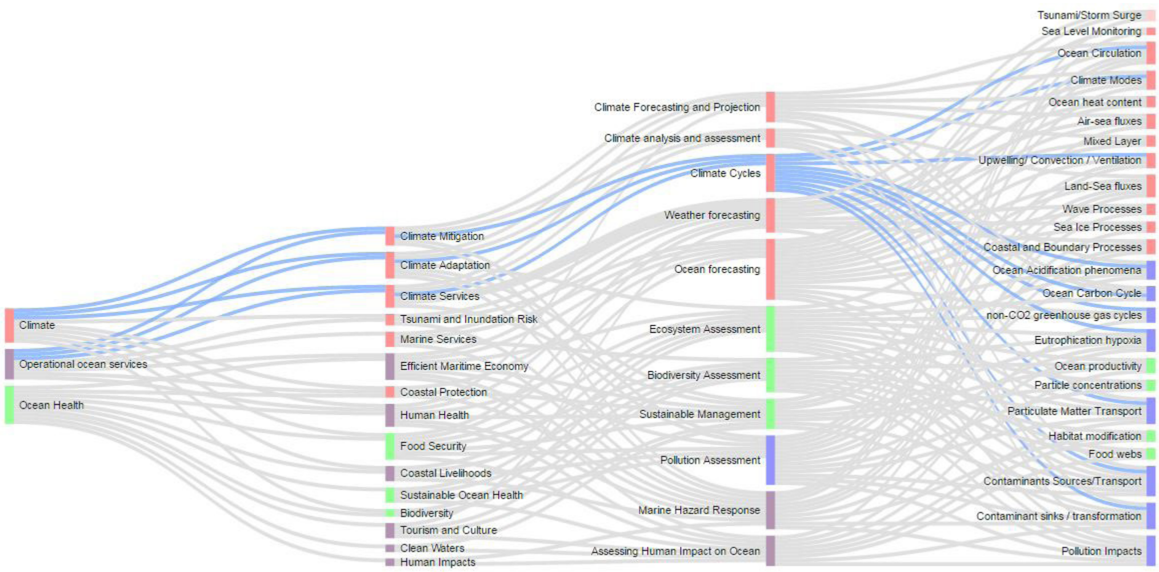


Table 3. Status of potential topic areas for future metrics.

Phenomena (Potential Metric Themes)	Status
Tsunami/storm surge	Uncollected
Sea level monitoring	Pilot Phase Completed
Ocean circulation	Uncollected
Climate models	Uncollected
Ocean heat content	Uncollected
Air-sea fluxes	Uncollected
Mixed layer	Uncollected
Upwelling convection/ventilation	Uncollected
Land-Sea fluxes	Uncollected
Wave processes	Uncollected
Sea ice processes	Uncollected
Coastal and boundary processes	Uncollected
Ocean acidification phenomena	Pilot Phase Completed
Ocean carbon cycle	Uncollected
non-CO_2 greenhouse gas cycles	Uncollected
Eutrophication hypoxia	Pilot Phase Completed
Ocean productivity	Uncollected
Particle concentrations	Uncollected
Particulate matter transport	Uncollected
Habitat modification	Uncollected
Food webs	Uncollected
Contaminants sources/transport	Uncollected
Contaminant sinks/transformation	Uncollected
Pollution impacts	Uncollected

CONCLUSION

Assembling metrics for ocean observing systems is not only essential for evaluating overall performance, but invaluable to decisionmakers and operators for guiding future developments. The exercise in collecting pilot metrics was valuable for determining how much effort is required to collect quality indicators. The IOOS enterprise, either through the Program Office, IOOC committee members, contractors, or some combination thereof, should invest in collecting high-quality, repeatable metrics. The pilot exercise demonstrated that substantial effort is required up front but should level-out over time. One immediate next step should be to have the IOOC Task Team collect the same pilot metrics again to measure how easily they can be replicated. Subsequently or in-parallel, additional thematic topics should be investigated or reviewed to determine level of maturity for expanding beyond the pilot metric topics. The IOOC must also assess the process and resources required for agencies to contribute towards those metrics and suggest ways to assess the impact of metrics on the target audience.

Based on this effort, establishing metrics beyond the pilot themes will require substantial coordination initially through one or more task teams relying on voluntary federal and nonfederal contributions, staff support, and meeting support for at least one in-person meeting and many virtual ones. The minimum investment to continue progress is $30,000 but increases beyond that amount will yield higher quality results proportional to the effort. One simple way to calculate an estimate for the optimal initial investment for establishing metrics across all 24 ocean observing phenomena is to multiply the $30,000 invested in this pilot phase for three themes ($10,000 per theme) by the number of themes - or $240,000. That would be the high-end initial investment, and then maintaining the collection of these metrics would normalize to half of a full-time employee or intern to update the text and figures each year.

In conclusion, the metrics established in this report demonstrate the potential for cross-agency analysis into their programs, providing two essential needs for agencies to meet their missions. First, is the ability to assess how well their ocean observing systems are performing. Second, is determining their progress towards addressing observing requirements. Meeting these two objectives ultimately provides decision-makers and other critical stakeholders a snapshot of the scope, value, and impact of ocean observing systems.

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