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The Challenge of Sustaining Ocean Observations

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Sustained ocean observations benefit many users and societal goals but could benefit many more. Such information is critical for using ocean resources responsibly and sustainably as the ocean becomes increasingly important to society. The contributions of many nations cooperating to develop the Global Ocean Observing System has resulted in a strong base of global and regional ocean observing networks. However, enhancement of the existing observation system has been constrained by flat funding and limited cooperation among present and potential users. At the same time, a variety of actors are seeking new deployments in remote and newly ice-free regions and new observing capabilities, including biological and biogeochemical sensors. Can these new needs be met? In this paper, a vision for how to sustain ocean observing in the future is presented. A key evolution will be to grow the pool of users, engaging end users across society. Users with shared values need to be brought together with commitment to sustainable use of the ocean in the broadest sense. Present planning for sustained observations builds on the development of the Global Ocean Observing System which has primarily targeted increased scientific understanding of ocean processes and of the ocean's role in climate. We must build on that foundation to develop an Ocean Partnership for Sustained Observing that will incorporate the growing needs of a broad constituency of users beyond climate and make the case for new resources. To be most effective this new Partnership should incorporate the principles of a collective impact organization, enabling closer engagement with the private sector, philanthropies, governments, NGOs, and other groups. Steps toward achieving this new Partnership are outlined in this paper, with the intent of establishing it early in the UN Decade of Ocean Science.

Keywords: sustained, ocean observation, partnership, shared value, society

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INTRODUCTION: THE VISION FOR SUSTAINED OCEAN OBSERVATIONS

Today, nations, the private sector, and many other sectors of society are looking to the ocean for more resources and expanded uses. The oceanographic community has recognized that understanding and adapting to climate change—with ocean impacts ranging from sea level rise to poleward shifts of valuable fisheries—will require additional monitoring of ecosystems and the biogeochemical and physical properties of the ocean. However, the drivers for sustained ocean

FIGURE 1 | The 17 sustainable development goals identified by the United Nations to build toward a better and more sustainable future and address the global challenges faced by society. (UN, 2018a)[1].

observations are much broader and the support developed to date for ocean climate observations is insufficient to support the sustained ocean observing system that is needed. Our focus here is to recognize these diverse needs and stimulate discussion of how to assemble these future users and motivate the higher level of support required.

The additional requirements for ocean observations come from activities that range from fishing to mining and from generating clean energy to finding new genetic resources. Experience has led to general agreement among the ocean constituency that following the UN Sustainable Development Goals will be essential for the future development of ocean resources. Of the 17 UN goals, just Goal 14 is focused on the oceans; but the goals for food, energy, infrastructure, cities and protection are also linked with the marine environment (**Figure 1**). At the UN Ocean Conference in June 2017, governments, the private sector, NGOs and most of the ocean community committed to working within such a framework. Achieving and maintaining sustainability requires a comprehensive base of information fed by long-term observations.

The specific targets in the ocean-focused Goal 14 (UN, 2018b)[2] are to:

1. Stop pollution
2. Manage and restore ecosystems
3. Minimize acidification
4. Stop illegal fishing
5. Conserve 10% of ocean areas
6. Stop fishing subsidies
7. Help small island states through sustainable management
8. Increase scientific knowledge.

Of these 8 targets, at least 6 would benefit directly from long-term observations: stop pollution, manage and restore ecosystems, minimize ocean acidification, stop illegal fishing, conserve 10% of ocean areas, and increase scientific knowledge. To be useful, more processes at more locations need to be monitored. New technology will be enabling, ranging from autonomous vehicles and artificial intelligence to new kinds of measuring instruments. But the main point is that if society is to operate in a sustainable mode, much more information from the ocean is needed.

The complex social, industrial, military, economic, and environmental landscape within which a wide range of communities interact to achieve these Sustainable Development Goals presents a challenge both for maintaining and expanding ocean observations. Within this landscape, though, there is immense opportunity for working together to achieve common goals of sustained ocean observations for the benefit of society. Such an effort would ensure coordination, communication, and shared agendas across multiple communities, and could result in a collective impact that exceeds the sum of the individual efforts at monitoring our oceans for the benefit of society. In this white paper, we outline a strategy for a new form of "Collective Impact Organization" (Kania and Kramer, 2011) that would inform a path forward for the support of sustained ocean observations.

In section The Social and Environmental Landscape we set the context of need for and benefit from sustained ocean observations by exploring the social and environmental landscape. In section The Foundation for Going Forward: The Present Approach to Sustaining Ocean Observations we summarize the present approach to sustaining ocean observations, pointing to the present international context for global ocean observations. Section The Future: An Ocean Partnership for Sustained Observations as a Collective Impact Organization presents our recommendation—a future ocean partnership for sustained observing, and sections Next Steps and Making OceanObs'19 a Stepping-Off Milestone outline the next steps that would lead to development of this partnership.

THE SOCIAL AND ENVIRONMENTAL LANDSCAPE

The 2017 consensus report by the National Academies of Sciences, Engineering, and Medicine (NASEM) on *Sustaining Ocean Observations to Understand Future Changes in the Earth's Climate* (National Academies of Sciences, Engineering, and Medicine (NASEM), 2017) (hereafter referred to as the NASEM 2017 report), recommended development of a clear, national-level plan for long-term ocean observing that is consistent with and complementary to international plans. Although ocean observing is a global enterprise, the U.S. has been a leader in both the development and implementation of observing systems, serving both domestic and international interests. Hence, development of a national-level plan in the U.S. would boost support for ocean observing globally. The report also supported the creation of an organization to promote partnerships across sectors to be called the Ocean Climate

[1]https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[2]https://www.un.org/sustainabledevelopment/oceans/

Partnership. The motivation for the NASEM 2017 report came from the recognition that a full understanding of the ocean's role in climate requires long time series of ocean variables. To realize the full value of these time series, there must be continuity, sufficient sampling frequency to avoid aliasing, and records with the quality and spatial resolution required to detect the signals of interest (Baker et al., 2007). For understanding climate processes, sustaining the measurements for many decades will be required; presenting a formidable, intergenerational challenge (Wunsch et al., 2013). Although the NASEM 2017 report is a substantive summary of these needs and challenges for climate observations, additional discussions during the development of the present white paper brought us to the conclusion that a broader global ocean partnership would better represent the spectrum of interests and values of ocean observing. Therefore, in this section, we focus on needs for sustained ocean observing in addition to those for climate.

Improving Weather Forecasting on Sub-seasonal to Seasonal Time Scales

Observations of sea surface temperature (SST) have long been utilized in routine short-term forecasting to initialize numerical weather prediction models. But now there is evidence that inclusion of additional ocean information will improve sub-seasonal to seasonal forecasts. Forecasts on this extended timescale will support advance planning in applications such as anticipation of droughts to inform farmers and water resource managers as well as to help reduce weather-related economic losses and increase protection of life and property (National Academies of Sciences, Engineering, and Medicine (NASEM), 2016). Continuing these improvements in forecasting skill will depend in part on additional observing information, such as sea surface salinity (SSS) combined with new technological approaches like using machine learning/artificial intelligence for enhanced data analysis.

The influence of SST on the patterns of atmospheric circulation have long been recognized and utilized for statistically—based seasonal forecasts (Namias, 1959, 1978; Palmer and Zhaobo, 1985; Kirono et al., 2010). Even longer timescales of climate variations (decades) have been fruitfully hind-cast using SSTs (Czaja and Frankignoul, 1999; Enfield et al., 2001; Ummenhofer et al., 2008, 2009). At seasonal and decadal time scales, the influence of the ocean heat reservoir has predictive value for atmospheric conditions. Similarly, numerical models can be run-out to about 1 week lead before the sensitivity to initial conditions degrades accuracy (the chaos effect). However, less is known about the sub-seasonal gap between 1 week and 3 months, where improving such forecasts is an active area of research (National Academies of Sciences, Engineering, and Medicine (NASEM), 2016; Zhu et al., 2017).

Artificial Intelligence techniques are now being applied to ocean data to improve seasonal and sub-seasonal predictions (Abbot and Marohasy, 2012; Li et al., 2018). Moreover, recent analyses indicate that SSS information adds surprising skill to seasonal predictions of rainfall on land (Li et al., 2016a,b). Teleconnections between SSS in certain oceanic regions and terrestrial rainfall one season later are likely due to the role of SSS as an indicator of the net moisture export from the ocean. Liu et al. (2018) find that SSS is superior to SST and other traditional climate indices for autumn lead predictions of winter precipitation in the US Southwest. This is just one example of advances in sub-seasonal to seasonal forecasting through the combined use of Artificial Intelligence tools and Bayesian statistical techniques applied to an expanding suite of ocean state variables. These advances are expected to have tremendous societal benefit at a time of intensifying storms, severe floods, and prolonged droughts.

The Blue Economy: Food and Mineral Resource Extraction

Can There be a Sustainable Blue Economy?

The World Bank defines the Blue Economy as "the sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health." A study by the OECD (OECD, 2016) estimated that the blue economy will double its fraction of global value added, outperforming the rest of the economy. The potential for growth throughout the blue economy will depend on the overriding principle that sustainability is at the heart of maintaining ocean resources and making them available to future generations. Society has learned that unless sustainability is built into resource management from the beginning, the environment suffers and living resources will decline (Roberts and Ali, 2016). Ocean users will be challenged to apply this to the development of new industries, such as deep-sea mining. In the Arctic, there will be an opportunity to apply these principles in a relatively pristine ocean as reduced summer sea ice opens this area for ice-free navigation for the first time in all of human history.

Fisheries

On a global basis, wild fisheries catch continued to rise through most of the Twentieth century as fisheries expanded into new regions and exploited ever more fish stocks. Then in the early 1990s, despite increased effort and fishing subsidies, wild fisheries catch began to level off at about 90 million tons/year. Since then, the major increases have come from farmed fish and other aquaculture (FAO, 2018)[3] (**Figure 2**).

As world population grows, nations are looking to find more food from the sea. But as we have seen from wild fisheries, we may be at the limit. Can the steady level of wild fish catch and growth of aquaculture continue? A fundamental part of the answer to that question is knowledge of the state and long-term changes in the marine environment. What natural fluctuations can we expect? How will climate change influence the habitat, locale, and productivity of fish stocks? Our knowledge of the changing environment and of global fish resources is still imperfect; the dynamics of many fish population remain uncharacterized. An effort to catalog our knowledge of marine biodiversity, the Census of Marine Life was first undertaken in 2000–2010 (Census of Marine Life, 2018)[4], underscoring how

[3]http://www.fao.org/state-of-fisheries-aquaculture/en/
[4]http://www.coml.org/about-census/

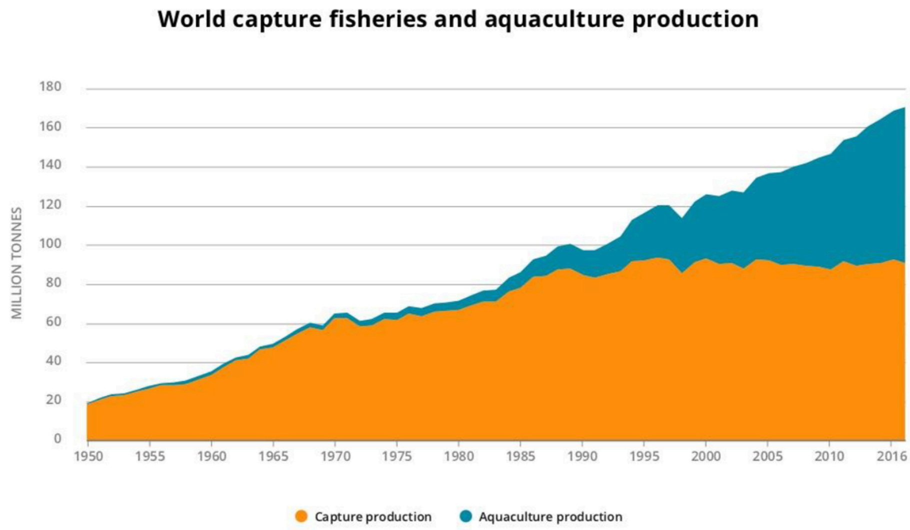

FIGURE 2 | Time history of fish caught and produced by aquaculture. From FAO, 2018.

much remains to be learned about the diversity and functional properties of ocean ecosystems.

New ways of monitoring marine ecosystems and marine biodiversity promise to revolutionize our ability to track invasive species, develop early detection of harmful algal blooms, monitor endangered species, assess the health of fish stocks, and explore the world of marine microbes. High throughput DNA sequencing has made it feasible and economical to analyze minute quantities of DNA in environmental samples. This has fostered the development of environmental DNA (eDNA) as a new "sensor" for monitoring marine biota. Because larger marine organisms shed DNA into the environment, eDNA allows detection of a species in a discrete (e.g., 1L) water sample without the requirement to capture or visually detect their presence (Hansen et al., 2018) and has proved to be an efficient way to monitor habitats (Yamamoto et al., 2017). Although eDNA provides exquisitely sensitive information about the presence and location of marine species, applications for assessing abundance, for example for fish stock assessment, are still unproven.

Passive acoustic monitoring—the detection of sounds emitted by marine organisms—provides another non-invasive approach for monitoring species and ecosystems (Van Parijs et al., 2009; Freeman and Freeman, 2016). Because acoustic signals propagate long distances in water, hydrophones can be deployed as a sensor to efficiently assess the distribution of animals that produce species-specific sounds, such as krill (Watkins and Brierley, 2002).

Deep-Sea Mining

In the latter part of the Twentieth century, the Law of the Sea Convention was put in place originally driven by the expected need for equitable allocation and recovery of deep-sea mineral resources. But the engineering challenges of profitable large-scale mining have limited investments. Now interest is growing: as of 2018, there are 29 approved contracts for exploration under the International Seabed Authority, and mining of critical materials may begin within the year (Pew Trusts, 2017)[5] But, since data from the deep-sea environment are so sparse, any mining that takes place will be done mostly in ignorance of the harm that might be done. Ideally there would be characterization of the seabed biota and ongoing observations of the marine environment around a potential mining site—both before the mining takes place, during the mining, and then afterwards. Otherwise, deep-water species and ecosystems may be damaged without awareness or appreciation of what has been lost. Extensive experience with land-based mining has shown the destructiveness of mineral extraction in the absence of effective environmental standards.

An Ice-Free Arctic Ocean

Sometime in the second half of the Twenty-First century, it is highly likely that climate change will cause the Arctic Ocean to become ice-free in the summer, opening it up to shipping, fishing, and drilling for oil and gas (Mahlstein and Knutti, 2012). Data collected over decades, especially to understand the ongoing changes as the Arctic warms, will be necessary to ensure that these new activities will in fact enable the sustainable use of the new resources, both mineral and living, that could be exploited.

Blue Economy: Non-extractive Resources

Genetic Resources/Biosynthesis/Medicines From the Sea

Most drugs have been developed from bioactive compounds found in plants, fungi, or microbes on land, but the discovery of new compounds has dwindled. The sea has been a source of anti-cancer compounds and antibiotics, and the search has become more urgent as the spread of multi-drug resistance

[5]http://www.pewtrusts.org/en/research-and-analysis/fact-sheets/2017/02/deep-sea-mining-the-basics

has crippled the efficacy of many current antibiotics. For example, corals and sponges have chemicals that can fight some of the most virulent bacteria (NOAA Medicines, 2018). The European Union is carrying out deep-sea sampling, genome scanning, chemical informatics, and data-mining to find more useful medicines (World Economic Forum, 2016)[6] Concomitant long-term observations of the relevant biological, chemical, and physical ocean environment are necessary to ensure that sources of potential new pharmaceuticals are not lost and are harvested sustainably.

Sources of Renewable Energy

The coastal ocean is home to large numbers of wind farms in Europe and offshore wind facilities are expanding in the U.S. and elsewhere. The long-term effects on marine biota of these relatively new installations are unknown. Experience from decommissioned oil rigs has indicated that the introduction of new structures increases substrate for sessile organisms and many fish species are attracted to structures, although the effect on fish abundance is largely unknown (Macreadie et al., 2011). But what is the long-term impact?

Of particular interest for providing power for coastal sensors and autonomous vehicles, the use of energy from tides and waves is expected to grow with the increasing demand for green energy (Yang and Copping, 2017). The same may be true of ocean thermal energy generation, based on the temperature difference between shallow and deep water. These technologies are feasible today, but only in a few places. However, demand for renewable energy sources could lead to an increasing number of structures for offshore wind and hydrokinetic energy capture. Long term observations will help in the selection of sites for installation and will provide environmental parameters for design specification and ecological monitoring. Planning is needed for effective placement of offshore energy activities, and knowledge is critical for the planning.

A longer-term effort is aimed at transforming microscopic algae into cells that take in CO_2 and become a source of biomass fuel. If feasible, this algae-based biofuel could provide many benefits. Although these operations are still in the research phase (Khan et al., 2018), any sustainable and low impact use of these techniques in open systems on a large scale will require long-term biological, physical, and chemical observations.

Reducing CO_2

Using iron fertilization to promote algal growth has been proposed as a strategy for sequestering additional atmospheric CO_2 (National Research Council (NRC), 2015). However, the fraction of CO_2 that remains sequestered in organic material (rather than being consumed and respired) has yet to be determined and there are serious concerns about the possible effects on ocean ecosystems. More needs to be known about carbon cycle in the ocean to estimate the potential for sequestration and assess the long-term impacts of large-scale fertilization. An alternative strategy is the conservation and restoration of coastal vegetation, often referred to as coastal blue carbon (NOAA, 2018a). This approach is based on the sequestration of organic carbon in sediments from marshes, mangroves, and seagrass beds. Evaluation of the long-term growth and stability of these coastal carbon stores will require additional monitoring.

Fresh Water From the Sea

The UN has warned that by 2050 the world is in danger of not having enough fresh water for the people who need it (UN Dispatch, 2017).[7] Despite the costs, coastal states are ramping up their desalination efforts; for example, Israel, Jordan, and Palestine just agreed to a plan to bring in and desalinate water from the Red Sea. Can the ocean solve the global freshwater crisis? Although costs have deterred major deployment of desalination plants in coastal states, the increasing water shortages may lead to more construction. What will be the impact on the coastal ocean from the deposition of concentrated brines? Monitoring should start now to establish a baseline.

Fleets of Autonomous Vehicles

Traditional users are rapidly adopting robotic technology, which will greatly expand the volume of the ocean which can be monitored and measured. Newly built internet infrastructure will make it easy to transfer data around the world. Shipping companies and navies are rapidly developing large autonomous ships, heavily dependent on artificial intelligence, to replace container ships and some naval operations. Fleets of robots could be useful for fisheries enforcement. These large vehicles will require large amounts of data to feed new artificial intelligence systems. Stone and Degnarain (2017) have suggested digital avatars connected to data sources and the Internet of Things that would run simulations based on large amounts of data—an idea similar to that of Henry Stommel's unmanned underwater gliders called Slocum Drifters (see e.g., Stommel, 1989). In any case, most of the data required will come from long-term ocean observations.

Coastal Development

Coastal development for housing, recreation, tourism, and shipping has an impact on the coastal ocean through destruction of habitat, sedimentation, and polluted runoff and air. Sustainable development will require monitoring and reduction of impacts on ocean and coastal ecosystems.

THE FOUNDATION FOR GOING FORWARD: THE PRESENT APPROACH TO SUSTAINING OCEAN OBSERVATIONS

Having presented examples of needs for sustained ocean observing in addition to climate, it is important to consider the development to date of sustained ocean observing, to acknowledge the progress that has been made, and then to highlight the challenges that the present approach has faced.

[6] www.weforum.org/agenda/2016/09/12-cutting-edge-technologies-that-could-save-our-oceans/

[7] https://www.undispatch.com/bad-news-world-will-begin-running-water-2050-good-news-not-2050-yet/.

Ocean observing capabilities matured greatly in the latter half of the Twentieth century and early Twenty-First century (**Figure 3**). The previous OceanObs'99 and OceanObs'09 conferences were milestones; these meetings and the intergovernmental efforts to establish a global ocean observing system, or GOOS, laid the foundation for our present sustained ocean observing efforts. **Figure 4** summarizes the state of the GOOS in March 2018 (Note that the small size of the figure gives the impression that the ocean is full of such observations; in fact, the spacing between measurements ranges from 3 to 5 degrees). Major contributions to the GOOS include: the Argo profiling float array of close to 4,000 floats; moored and drifting buoys, sustained time series sites, usually moorings coordinated by OceanSITES; ship-based repeat hydrography through GO-SHIP; shipboard sampling along lines repeated every 5 to 10 years; tide gauges; and ocean and meteorological sampling from merchant ships.

To a large extent the work to develop a GOOS was motivated by the need to better understand the role of the ocean in climate and to develop improved predictability at interannual and longer time scales.

The Motivation for the Present Approach to Sustained Ocean Observing

Sustained and uninterrupted ocean observations are vital to understanding the state and trend of many physical, chemical, and biological components of the Earth system. The ocean has absorbed 90% of the surplus heat (Rhein et al., 2013) and about 30% of the excess CO_2 released by anthropogenic activities (Ciais et al., 2013). It receives close to 100% of the freshwater lost from land ice. The deep ocean is a long-term reservoir of these components, and observations must occur over long time scales to capture this. Time series of observations need to be collected at a frequency sufficient to capture subseasonal, seasonal, and longer time scale patterns. Gaps in observations, once lost, cannot be restored. The NASEM 2017 report, for example, identifies the value of ocean observing in closing three global budgets for climate: heat, carbon, and fresh water. Changes in the Earth's climate also threaten ocean ecosystems. In order to track the impact of the changing climate on ocean biodiversity, observations are critical. Notably, coral reefs and shellfish are impacted by increasing acidity of the ocean and warming waters alter and reduce the range of valuable fisheries species.

Sustained ocean observations are also critical for understanding and predicting phenomena beyond climate that have consequences for the economy and society. The same platforms that provide critical climate information can be used to provide a broader set of benefits. Foremost, modern weather forecasting, including hurricane formation and intensity as well as seasonal precipitation, is reliant on temperature and current observations in the ocean. The Tropical Pacific Observing System (TPOS), which measures long-term changes in ocean-atmosphere heat exchange, was originally designed to better understand and predict the El Niño–Southern Oscillation (ENSO) phenomenon. TPOS has provided vital data to improve ENSO forecasts for decisions about agriculture, for example (Hansen et al., 1998; Chiodi and Harrison, 2017). Following the TPOS model, ocean observing systems have been developed for the Atlantic (PIRATA) and Indian Ocean (RAMA).

Progress in the Present Observing System

A wide variety of institutions and sectors have participated in the development of the present international ocean observing enterprise. Ocean observing is an end-to-end system, consisting of engineering, operations, data management, information products, and workforce, supported by planning and governance at national and international levels. The global observing system that stands today is the result of an internationally coordinated set of organizations and platforms. Global observations are coordinated under GOOS, an organization

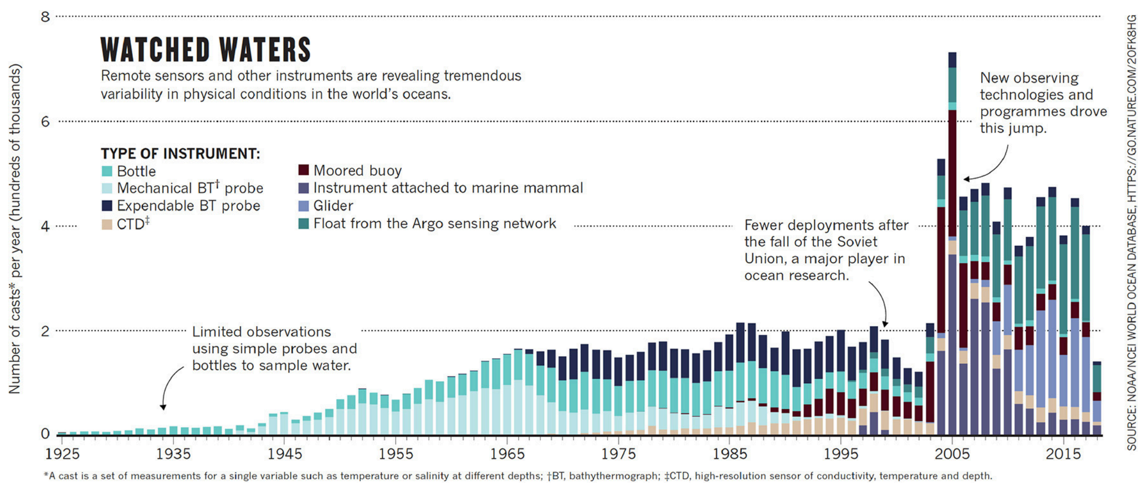

FIGURE 3 | The growth of the number of temperature and/or salinity profiles per year since 1925. The type of data is coded by the colors. Relatively steady levels of ocean sampling held from the mid-1960s to the mid-2000s, when new technology roughly doubled the number of profiles obtained from near 200,000 per year to 400,000 per year. Figure from Bates et al. (2018).

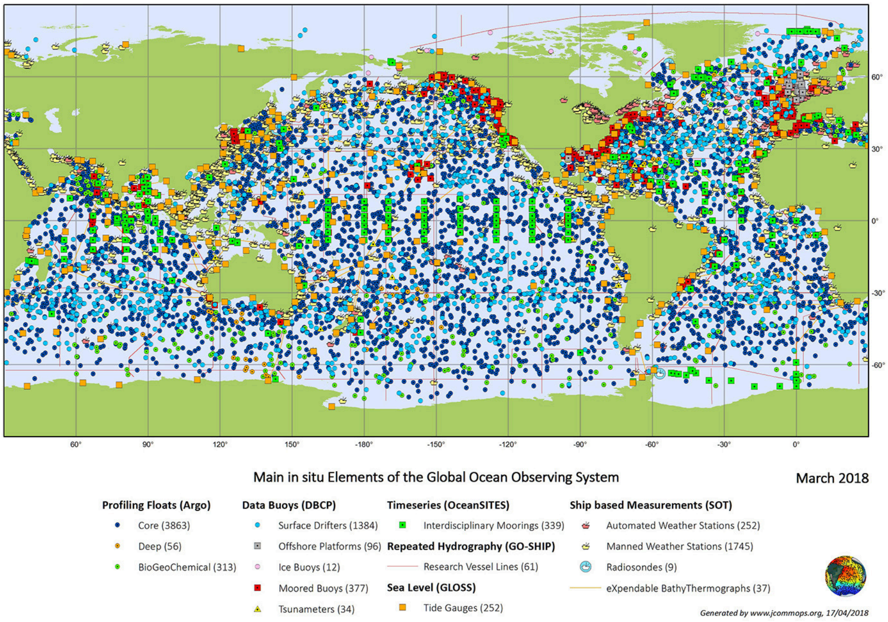

FIGURE 4 | The status in March 2018 of the elements of the GOOS, as tracked by the Joint Technical Commission on Marine Meteorology (JCOMM)[8]. Updated monthly summary maps available at JCOMM, 2018 (http://www.jcommops.org/). The dots representing platform locations are sized to be visible, but the actual coverage of the ocean remains sparse.

of the Intergovernmental Oceanographic Commission (IOC). GOOS supports observations in three thematic areas: Climate, Operational Ocean Services, and Ocean Health. Implementation of the global observing system is guided by the Framework for Ocean Observing (FOO; Lindstrom et al., 2012), a science-driven process for identifying priority observations and requirements that address societal needs. Ocean observations are also one component of climate observations organized under the Global Climate Observing System (GCOS). GOOS and GCOS are supported by expert panels that develop standards for observations of variables, the Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs), respectively. The Ocean Observations Panel for Climate (OOPC) is the expert panel for physical variables. The FOO allows the ocean observing system to evolve based on technology advances and emerging research needs, strengthened by input from expert panels and other scientific associations, as well as the research community as a whole.

GCOS and GOOS draw on the expertise of the oceanographic and climate science community to advise the implementation of ocean observations. The development of observing requirements for EOVs and ECVs is guided by expert panels. EOVs (and the ocean-based ECVs) fall into three categories, with associated panels: Physics, Biogeochemistry, and Biology and Ecosystems. For example, the Physics panel built on the pre-existing International Ocean Carbon Coordination Project (IOCCP), which promotes and coordinates ocean carbon observations. Another important entity for facilitating observations, analyses, and predictions of changes in the Earth's climate system is the World Climate Research Program's (WCRP) CLIVAR (Climate and Ocean: Variability, Predictability and Change). CLIVAR also carries out short-term, intense sampling during process studies. The role of the WCRP and of the expert panels such as the OOPC are discussed in related OceanObs'19 papers.

Many nations now contribute to sustained ocean observing. Within the United States, Federal agencies engage in the intergovernmental negotiations at the international level, and are the primary supporters of ocean observing activities through funding for research, technology, and operations. Key agencies include the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Office of Naval Research (ONR). Federal activities are coordinated through subcommittees and interagency working groups under the National Science and Technology Council. Federal agencies fulfill their contribution to GOOS through the U.S. Integrated Ocean Observing System (IOOS). Federal and nonfederal contributions to IOOS are organized by NOAA in consultation with the Interagency Ocean Observations Committee (IOOC), which conducts the activities related to IOOS planning, policy, and coordination. Agencies can cooperatively fund ocean research through the National Ocean Partnership Program (NOPP) and coordinate through the National Ocean Research Leadership Council. For instance, NOPP facilitated the partnership between the U.S. Navy and NOAA in the development and implementation of the U.S. Argo program and ocean prediction systems with the HYCOM

[8]http://www.goosocean.org/index.php?option=com_content&view=article&id=21&Itemid=271

modeling initiative. Furthermore, NOPP facilitated public-private support from NSF and the Packard Foundation for development of the Environmental Sample Processor—an important advance in automated water sampling for molecular approaches to biological monitoring, such as eDNA applications, as well as development of other new platforms and sensors (Lindstrom et al., 2009). NOPP supports the Marine Biodiversity Observation Network (MBON), which provides a portal for biodiversity information, including eDNA and more traditional datasets (http://www.marinebon.org/our-work.html). The track record of NOPP provides useful lessons that could inform the development of public-private partnership organizations in other countries.

In many ways, **Figure 4** represents a remarkable achievement in the creation of a new observing system. However, financial pressures on the nations and national agencies providing the on-going support are evident. For example, NOAA's IOOS Regional Observations and Sustained Ocean Observations and Monitoring programs have been essentially flat-funded over the past 5 years. Sustained Ocean Observations and Monitoring, which funds the U.S. Argo, would suffer an 11% decrease if the President's FY 2019 budget is enacted (NOAA, 2015, 2018b). At present, there is a study of the TPOS aimed at examining how to go forward with reduced contributions to the array; and some nations have terminated elements of observing arrays, such as the Southern Hemisphere sites of NSF's Ocean Observatories Initiative.

Ocean Data in the Hands of Users

The value of sustained observations is only realized when data and derived information products are made available to users. Data collected under GOOS are made freely available for users through Data Assembly Centers (DACs). DACS also play a role in unifying various data streams being collected. However, at present, global distribution of data in real time is limited. Data must be collected from a variety of DACs, dependent on the platform it was collected from. Additionally, many users are not traditional users of NetCDF or ASCII data formats. There is an opportunity to increase data access globally.

Additionally, there is a need for frameworks to synthesize data from diverse sources in order to develop data products that provide more detailed knowledge of the Earth system. Data assimilation models have been developed for weather prediction, and are gaining use for a broader range of consumers. The sparsity of ocean observations has made implementation of data assimilation frameworks difficult. Continuous global ocean observations are needed to develop robust data products for predicting weather, climate trends, and other uses.

Challenges of the Present and Future Opportunities

The NASEM 2017 report highlighted several challenges facing sustained global ocean observations. The readiness of biological and ecosystem observations lags behind those for physical and biogeochemical variables. Some important processes are insufficiently measured, such as fine scale mixing. The deep ocean is a long-term reservoir of heat and carbon, but few platforms reach these depths to allow quantification. There is also a lack of consistent deployment of observing platforms within Exclusive Economic Zones (EEZs). About 30% of the global ocean lies with EEZs and other maritime zones, and thus, deployment in these zones is necessary for global coverage. This will require participation from and partnership with many nations. However, lack of trained personnel, particularly in developing countries and nations with economies in transition, limits expansion of a globally coordinated observing system (POGO (Partnership for Observation of the Global Oceans), 2018). Initiatives to build capacity globally have played a role in involving a greater number of countries in ocean observing implementation and planning. One example of the type of programs that have been effective in supporting capacity building for ocean observing is the Partnership for Observation of the Global Oceans (POGO). Another example is the International Oceanographic Data and Information Exchange Programme (IODE) which promotes collection, exchange, and access to oceanographic data and information, in part by assisting nations in acquiring the expertise to become partners in IODE and support the Framework for Ocean Observing (IOC-UNESCO, 2017).

To illustrate the challenges, we note that in the U.S., federal and academic research institutions oversee a significant portion of the national contribution to the global observing system. This workforce provides the engineering, technical, and research expertise to improve, implement, and create data products for the ocean observing enterprise. Some nonprofit and philanthropic organizations support ocean observing by providing funding for conservation research and technology. Private companies play a role developing technology and data tools, as well as serving as a user of observational data and data products. Coordination across this range of stakeholder is vital for advancing ocean observing. However, within the United States, government agencies are the primary source of support, and challenges in sustaining funding for ocean observing threaten U.S. contributions and threaten the stability of consistent data collection. Annual budget cycles and short-term grants may result in discontinuity of ocean climate measurements, reducing the value of the observations made to date and in the future.

The ocean is a physically harsh and logistically complex environment for the collection of observations. Observing platforms corrode in seawater, are subject to biofouling, and must withstand cold water and high pressures. Seawater is opaque to radio frequencies, making remote communication of data difficult. Platforms rely on low-powered, durable electronics so they may last for long periods in remote areas of the ocean without maintenance. Current and near-future technologies, particularly related to batteries and autonomous platforms, have helped address ocean observing challenges. However, U.S. investments in technology have diminished since the 1980s. Despite expected advancements in technology, global and ocean class ships will be necessary to maintain platforms and collect some types of observations. A decreasing national fleet puts this capability at risk.

Gaps remain in the current observing system that must be filled, such as data-sparse regions in the Southern Ocean and Southeastern Pacific. Some observations, like ambient noise, which includes signals from wind and rain as well as from marine organisms, human activities, and other sources, are not now commonly collected but in the future passive acoustic sensors could be deployed on may platforms. With sufficient support in the future, ocean observing programs will evolve as improvements in technology increase observing capabilities, and as changes in the Earth system necessitate new observing requirements. Increasing ice-free summers in the Arctic Ocean, for example, will open up more surfaces to be monitored. The GOOS expert panels, including the OOPC for physics and the biogeochemical and the biology and ecosystems panels, will continue to guide the development of the observing system under foci that are primarily driven by science, including climate. International and national research programs, including the WCRP, CLIVAR, and others, will contribute advancements in technology and knowledge that will also guide the evolution of the observing system. The resulting desire to sample with new sensors that require additional power and platforms further challenges the present efforts.

THE FUTURE: AN OCEAN PARTNERSHIP FOR SUSTAINED OBSERVATIONS AS A COLLECTIVE IMPACT ORGANIZATION

The development of sustained ocean observing for climate has had success, but now faces challenges and future growth is uncertain. Adding on the broader needs presented in Section The Social and Environmental Landscape, we believe that a new strategy is needed and present a proposal for an Ocean Partnership for Sustained Observations.

As part of a new approach, a long-term plan, with a framework for partnerships with stakeholders, is needed. The NASEM 2017 report identifies the value of a formal partnership to increase engagement and coordination of the ocean observation science community with nonprofits, philanthropic organizations, academia, U.S. federal agencies, and the commercial sector. The importance of ocean data for national security, the economy, and society, as well the international coordination required to support a global system, makes the federal government primarily responsible for supporting ocean observations. However, there is an opportunity for new models of support of a sustained observing system within and beyond federal structures.

Long-term planning and partnerships with private and nonprofit sectors could address some of the challenges in maintaining sustained observations nationally. This includes support for workforce, technology development, deep ocean moorings and global and ocean class ships. Shell's Stones Deep-Water Project is a recent example of a partnership to collect long-term deep ocean data that utilizes infrastructure for oil and gas development for ocean observing. Current collaborators with Shell on the Stones Metocean Observatory Project include the University of Southern Mississippi, Texas A&M University, Fugro, the National Oceanic and Atmospheric Administration, and the NASEM Gulf Research Program (http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=11142018).

There is a challenge in supporting early technical, engineering, and research staff. Metrics for academic promotion such as a large number of publications are not aligned with the long-term nature of ocean observing, particularly for climate. Observational data for climate takes years to collect, and because it is often made freely available, young scientists have little incentive to initiate or sustain long time series given the career demands for rapid publication of novel research results Scientists are also hindered by the lack of research positions that provide long-term funding stability. This threatens the continuity of the workforce to sustain ocean observing in the future.

Bringing Users Together Under Shared Values

What is needed for the future? Governance and protection require all relevant players to be at the table for policy decisions. Policy decisions must be underpinned by the right science and smart, innovative financial models. Partnerships and collaborations within and between nations are central to success. Enforcement is essential. A new model of successful international governance is one that is fed by science and supported for implementation not only by policy makers but also by business executives, local communities and financial institutions.

New Paradigm for Support of Sustained Ocean Observations

The Need for a New Cooperative Approach

As mentioned at the beginning, while the NASEM 2017 report specifically suggested an Ocean Climate Partnership, it is clear now that to achieve the Blue Economy and support the growing breadth of ocean activities and interests, it is more appropriate to build toward a broader international Ocean Partnership for Sustained Observing (OPSO). Such a partnership would be an effective mechanism to increase engagement and coordination of the ocean observation science community with non-profits, philanthropic organizations, academia, U.S. federal agencies, and the commercial sector. Through their shared interests in the observational data and associated products, the OPSO members would work together toward the goal of sustaining an ocean observing system for climate and other sustainability purposes.

But to get from here to there will require new cooperation beyond what has been achieved to date. Up to recently, the many ocean organizations that do exist have tended to operate more on their own than jointly. Just one illustrative example can be seen with the broad mandate of the UN, which covers ocean science, shipping, dumping, biodiversity, fisheries, mining, the Arctic, and more (**Figure 5**). This broad mandate emphasizes the importance of new and growing uses of the ocean.

NGOs such as Oceana, World Wildlife Fund, Conservation International, and many others have developed effective programs and are strong on raising awareness. Foundations have tended to focus on a narrow range of internal interests and the private sectors works within the scope of specific business models. But there is increasing awareness of the need for more data from all of these sectors. For example, the World Economic Forum's World Ocean Forum has already stated that: "We need

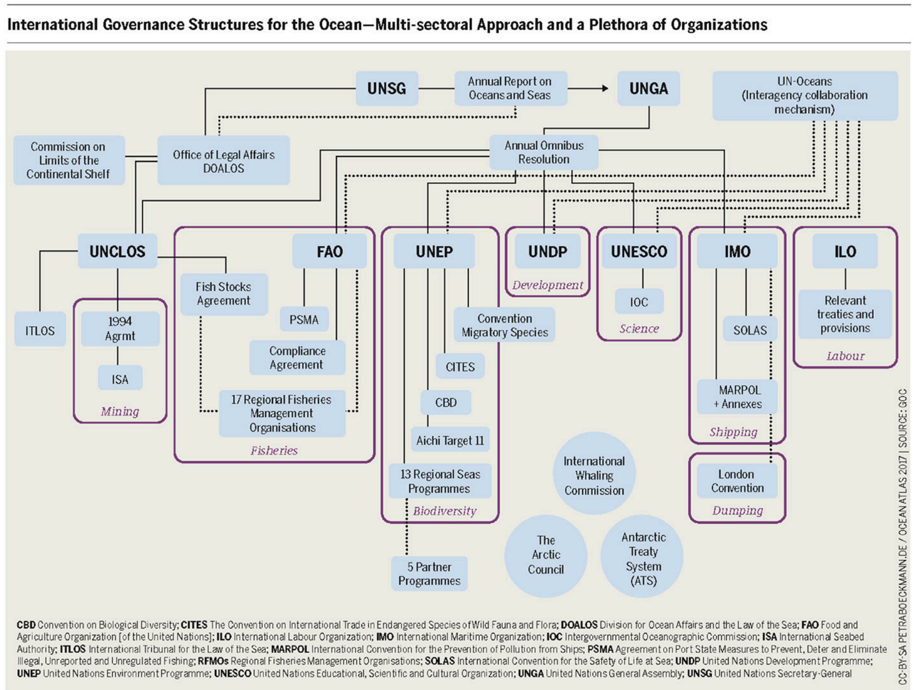

FIGURE 5 | UN Mandates for Ocean-Related Activities (UN Ocean Structure Atlas, 2017)[9].

much more data at higher frequency, quality, and variety to understand our oceans to the degree we already understand the land. Less than 5% of the oceans are comprehensively monitored. We need more data collection capacity to unlock the sustainable development potential of the oceans and protect critical ecosystems." (World Ocean Forum, 2017) [10]

We want to focus here on how best to bring these many interests together and move forward on stronger support for ocean observations. Below we outline the collective impact approach, then show some examples of collective impact organizations that have been successful, relate these ideas to existing atmosphere and ocean organizations, and conclude with ideas for the Ocean Partnership for Sustained Observations.

The Collective Impact Organization

An important emerging concept is that of the *collective impact organization* approach to address broad issues with many constituencies. This new approach arises from the realization that the complex nature of most social problems makes it difficult for any single program or organization, however well managed and funded, to single-handedly create lasting large-scale change. In such collective organizations, the participants share a vision of change and a commitment to solve a problem by coordinating their work and agreeing on shared goals. Participants agree to shared core values and agenda, share metrics for success, support mutually reinforcing activities, provide continuous communication, and have an agreed-on backbone support organization (**Figure 6**).

In such an organization, the *shared agenda and set of core values* should be initially established by the contributing organizations. The shared agenda should be broad enough that different contributors will contribute in very different ways to an overall effort yet provide boundaries that ensure the effort is overly ambitious. For ocean observations, examples of shared values might include "sustained observations," "open access to data," or "observations for the benefit of society." Such core values should be decided upon by the community of contributors and should involve listening sessions within the various contributing and stakeholder communities. These core values provide guidance for a shared agenda, and a platform for defining metrics of success.

Shared metrics of success provide an opportunity to evaluate whether actions taken by the organization (or contributing organizations) are contributing to the overall agenda, despite unique contributions from each of the contributors. For example, a core value of "open access to data" suggests that a metric of success would be the amount of collected data that is easily accessible. While each organization may have different objectives, it is important that a broad enough set of metrics exist that each organization can determine and evaluate its contribution to the overall effort. These metrics are decided upon by the advisory boards, but should be collected by the backbone organization.

In order for collective impact to be greater than the sum of its parts, coordination is needed to ensure

[9]https://www.boell.de/sites/default/files/web_170607_ocean_atlas_vektor_us_v102.pdf?dimension1=ds_ocean_atlas
[10]https://medium.com/world-ocean-forum/how-data-can-heal-our-oceans-e80a3e817b22

The Five Conditions of Collective Impact	
Common Agenda	All participants have a shared vision for change including a common understanding of the problem and a joint approach to solving it through agreed upon actions.
Shared Measurement	Collecting data and measuring results consistently across all participants ensures efforts remain aligned and participants hold each other accountable.
Mutually Reinforcing Activities	Participant activities must be differentiated while still being coordinated through a mutually reinforcing plan of action.
Continuous Communication	Consistent and open communication is needed across the many players to build trust, assure mutual objectives, and create common motivation.
Backbone Support	Creating and managing collective impact requires a separate organization(s) with staff and a specific set of skills to serve as the backbone for the entire initiative and coordinate participating organizations and agencies.

FIGURE 6 | A summary of the five conditions they listed to be met for a collective impact organization. From Hanleybrown et al. (2012).

that different *efforts are mutually reinforcing*. For example, needs for new oceanic parameters to be measured for scientific discovery may motivate research and development of new instrumentation by private business. The organization should look to capitalize on these feedbacks between activities of the different contributing organizations.

Continued communication is necessary for buy-in among the different organizations, and to provide a sense of legitimacy to the various communities that are being served by the organization. There should be several layers of communication here. The first is at an advisory level, through established advisory boards that adjust the shared agenda, and set strategic planning goals. A second level of communication is required among the different participants in the organization to ensure coordination between efforts. And a third level of communication is outward facing, and ensures that efforts of each participating organization, as well as the effort as a whole, are being communicated to the broader communities and stakeholders that are served by the activities of the organizations.

Finally, it is important to emphasize that the *backbone support organization* is key to the success of efforts at developing collective impact. The importance and role of the backbone organization is outlined in papers by Turner et al. (2012), and include guiding the vision and strategy, coordination and support for the aligned activities, tracking metrics of success, communicating results, and mobilizing funding. While the backbone organization is critical for carrying out the vision and strategies, it should not dictate the agenda or the core values (though membership should be involved in such discussions). The backbone organization also serves to facilitate communication at various levels (described above).

Examples of Successful Collective Impact Organizations

We believe that the general concepts of collective impact organizations can be applied in the ocean observations context, and provide here two examples of collective impact organizations that show how the concept can be effective both with programmatic institutions and with philanthropies.

Wisconsin Initiative on Climate Change Impacts (WICCI)

The Wisconsin Initiative on Climate Change Impacts (WICCI, 2018)[11] was founded consistent with collective impact principles to deal with the fact that climate variability and change impact society in ways that can rarely be understood with a disciplinary, or linear approach. It arose from the need for interdisciplinary settings in which interactions between different disciplines are necessary for defining disciplinary knowledge gaps, addressing those gaps, and assimilating information in order to address specific problems.

WICCI's organizational structure follows very closely the literature on Collective Impact Organizations (Kania and Kramer, 2011) and complex-adaptive systems. Consistent with collective impact, WICCI is a broad, semi-open, decentralized network that is served by a centralized, non-prescriptive infrastructure. This approach is especially powerful because it is inclusive (the open network approach), adaptive (as new research needs emerge WICCI easily connects with existing expertise), and preserves autonomy of the participating individuals and groups (this avoids issues of "territory" and attribution). It is also important to note that WICCI exists as an organization within a constantly evolving complex adaptive system. In such a system, one role of the organization is to ensure that new ideas and needs are identified and communicated within the

[11] http://www.wicci.wisc.edu/

network and with relevant outside expertise (Rammel et al., 2007). WICCI accomplishes that role using a variety of methods across a hierarchy of scales that follow many of the ideas found in research on complex adaptive systems and collective impact. Ultimately, WICCI has been very successful in enabling climate adaptation in Wisconsin and the region, including contributing to K-12 educational materials, developing decision support tools for coastal management, evaluating infrastructure decisions for storm water management, community planning, providing a scientific basis for WDNR land priorities, and much more.

Experience with WICCI has shown that any broad-scale effort should be inclusive of existing disciplinary and interdisciplinary research and decision-making activities, and should bring value to those efforts. It emphasizes that no single approach is optimal for addressing specific climate impacts. Instead, it focuses on a diverse set of approaches that allow specific efforts to move forward in ways that best meet the needs and constraints of the situation.

ClimateWorks

ClimateWorks (2018)[12] is an example of an organization that sees itself as a "catalyst for collective impact." It was established in 2008 by the William and Flora Hewlett Foundation, the David and Lucile Packard Foundation, the Energy Foundation, the Doris Duke Charitable Foundation, the Joyce Foundation, and the Oak Foundation to explore how philanthropy could have greater impact in the effort to mitigate dangerous climate change (see ClimateWorks., 2008). That report identified priorities for intervention globally and charted a course for climate philanthropy. During the first 6 years, ClimateWorks made hundreds of grants worldwide, helped build capacity in key regions, and collaborated with a network of partners to support research, policy advocacy, outreach and public engagement, all with the aim of reducing the emissions that cause climate change. These successes confirmed that strategic philanthropic investments could help shape public policy, private sector engagement, and public support, hereby helping to reduce carbon emissions, at scale. ClimateWorks' global scope and focus on key regions were also important strengths.

In 2013, ClimateWorks began to engage with broader networks of partners, share strategies and knowledge more widely, and support more coordination among funders. The group took on a bigger role to help leading climate funders coordinate and worked with partners around the world to grow climate philanthropy and reduce the emissions that cause climate change. ClimateWorks shows how the collective impact approach can have an important impact on society's need to move toward a prosperous, sustainable, low-carbon future.

Some Existing Meteorological and Oceanographic Organizations Considered in the Context of a Collective Impact Organization

Existing coordinating bodies

In the U.S., organizations to support ocean observations can be traced back to the 1990s with the development of the U.S. contribution to the nascent GOOS. In 2000, the Ocean.US office was established to support development of the national ocean observing system. These early efforts gained traction after a workshop at Airlie House in 2002 that coalesced around a vision for an Integrated Ocean Observing System (IOOS;Ocean US, 2002). The vision identified 7 areas of societal benefit that would guide IOOS:

- Detecting and forecasting oceanic components of climate variability
- Facilitating safe and efficient marine operations
- Ensuring national security
- Managing resources for sustainable use
- Preserving and restoring healthy marine ecosystems
- Mitigating natural hazards
- Ensuring public health

Since then, U.S. IOOS has developed into two components: the US contribution of open ocean observations to GOOS and a domestic coastal program. The latter is organized as a national-regional partnership that works "to provide new tools and forecasts to improve safety, enhance the economy, and protect our environment." In 2009, IOOS became authorized under the Omnibus Public Lands Management Act and the program office was established in NOAA's National Ocean Service, becoming the official U.S. IOOS program office in 2011. Through the national-regional partnership, each region develops a program of observations to address local needs within standards set by the national program.

The IOOS Association, formerly known as the National Federation of Regional Associations for Ocean and Coastal Observing (NFRA), provides an example of a non-governmental, non-profit organization formed to advance ocean observing efforts, in this case for the coastal ocean observing programs run through a regional-national partnership. The IOOS Association has been an important part of the progress made in implementing IOOS. Early organizers of the regional programs recognized that the need to organize themselves to promote collaboration, communication, and integration, and to develop a collective voice to support the national commitment to the program. Therefore, this association of the regional programs represents a type of collective impact organization that pools the shared interests and energies of the individual regional programs in support of US IOOS. The IOOS Association includes 11 IOOS Regional Associations (http://www.ioosassociation.org/about)

Other oceans groups that have contributed to the development and support of ocean observing systems include POGO, made up of representatives from major ocean institutions from around the world, and the Consortium for Ocean Leadership, an organization that advocates for ocean science and technology with a membership of predominantly academic institutions, but with important representatives from industry, aquaria, and non-profits.

The global weather enterprise (GWE)

A useful analog for the ocean observing community is the Global Weather Enterprise which provides for daily weather forecasts and much more for the world. Although not

[12] https://www.climateworks.org/about-us/our-history/

designed as a Collective Impact Organization, it has many of the same characteristics. In the Enterprise arrangement, the public, private and academic sectors cooperate for mutual benefit. This Enterprise is most mature in the U.S. where the American Meteorological Society has played an important role as a neutral host for discussions and planning to further the enterprise (see AMS, 2017)[13] The scope includes observations, forecasting services, business development, and policy development. Examples of tangible benefits of the Enterprise include private companies lobbying to maintain observing infrastructure, seamless cooperation in severe weather events, technology transfer, and broader career opportunities for students.

In recent years, the UN World Meteorological Organization has been promoting the Global Weather Enterprise. The urgency to do this comes from the need to be even more effective in saving lives and protecting infrastructure because of vulnerability to weather hazards in a changing climate and the rapid advance of technology that is more readily adapted by private companies. All participants in the Enterprise recognize there is a strong need for more science, observations, and computing power to improve weather forecasts. Moreover, the context for the weather enterprise is evolving rapidly today as improvements in technology, including those driven by other industries, are creating exceptional opportunities to deliver even higher quality weather forecasts. Continuing public sector investment in both weather science and in the global observing system is viewed as essential (WMO, 2016).[14]

Just as the Global Weather Enterprise supports many different needs, the global ocean observing systems must support many different needs. And just as the Global Weather Enterprise builds strong collaboration and has good support from both the public and private sectors, global ocean observing systems must also look for increased collaboration and diverse funding. It is the combination of needs, ranging from science and understanding to all of the data needed to bring sustainable management to ocean resources, which must be mobilized to support the ocean observing system. Could there be a Global Ocean Enterprise?

Public-Private Partnerships

Today we are seeing new private sector coalitions and public-private partnerships being formed. In general, ocean organizations are beginning to find that more collaboration and joint projects are more effective in accomplishing real results. Two useful examples are the *World Ocean Council* and the *World Economic Forum's New Vision for the Ocean*. The World Ocean Council was founded in 2008 as global, cross-sectoral ocean industry leadership alliance to bring together leaders of corporations, industry and trade associations, as well as research, academic, and scientific institutions with a commitment to the future of the ocean (World Ocean Council, 2017).[15] The WOC is committed to corporate ocean responsibility and is taking a multi-sectoral approach to address cross-cutting issues affecting ocean sustainable development, science, and stewardship of the seas. The interests of the WOC members shows its breadth: shipping, oil and gas, fisheries, aquaculture, tourism, renewable energy (wind, wave, tidal), ports, dredging, cables, as well as the maritime legal, financial and insurance communities, and others. They have a commitment to ensuring that the ocean business community's role in ocean sustainable development is understood by all relevant stakeholders (decision makers, policy makers, intergovernmental bodies etc.).

The World Economic Forum's New Vision for the Ocean (NVO) project (World Economic Forum, 2018)[16] supports a range of initiatives and events from the public and private sectors to ensure the long-term sustainable use of the ocean. Designed to help advance SDG 14, the New Ocean Vision offers a platform for key industries to work together with government, civil society and the scientific community on implementation and accountability. It has three primary objectives through 2020: (1) work with the UN to help shape and drive an action track for SDG 14, (2) Mobilize a cross-sectoral "Friends of Ocean Action" group to advance the Ocean Action Track, and (3) Mobilize additional finance in support of the Ocean Action Track by identifying and pursuing funding from philanthropic organizations, donor agencies and high net worth individuals in support of the Ocean Action Track.

An interesting analog for what the ocean community might try to do is Mission Innovation, a clean energy venture launched at the Paris Climate Conference in 2015. The program is a global initiative of 23 countries and the European Union, representing 70% of the world's GDP and 80% of government investment in clean energy research. The members of Mission Innovation have committed to taking action to double their public clean energy over 5 years. To that end, Mission Innovation members are encouraging collaboration among partner countries, share information, and coordinate with businesses and investors. Mission Innovation is complemented by private sector-led investments in clean energy, focusing on early-stage innovations (Mission Innovation, 2017).[17] Several multi-million dollar programs are in the works.

As the UN agencies and the ocean community build momentum for the UN Ocean Conference in 2020, it would make sense for the Ocean Partnership for Sustained Observations to explore similar options to Mission Innovation for linking to the private sector.

It will be important to invite these new private sector groups to coordinate with existing groups noted above such as IOOS, the Consortium for Ocean Leadership, CLIVAR, POGO, and others. This will build a full set of users to strengthen coordination and to fund and implement an enhanced ocean observing system.

We envision the Ocean Partnership for Sustained Observations as a collective impact organization. It would bring together the main partners now involved in ocean observations, and the key users. Given the extensive work that has already been done on science and essential ocean

[13]https://www.ametsoc.org/cwwce/
[14]https://public.wmo.int/en/resources/bulletin/weather-enterprise-global-public-private-partnership
[15]https://www.oceancouncil.org/
[16]https://www.weforum.org/projects/a-new-vision-for-the-ocean
[17]http://mission-innovation.net/

observations, the focus of the Partnership would be on funding and implementation. Here we focus on new opportunities for cooperation and funding.

The Ocean Partnership for Sustained Observations—A Focus on Coordinating Funding and Resources

Real progress on any of the issues discussed in this white paper requires a combination of improved coordination among users, continuation of existing funding commitments, and new resources for essential enhancements of the observing system. The NASEM 2017 report has underlined the importance of substantial institutional support and the need for guarantees of long-term funding. But, it also notes that overall funding has been flat for about a decade. It points out that annual budget approvals, unpredictable funding streams, and short-term grants are already leading to discontinuity of measurements. Better coordination among users and additional funding from a variety of sources will be required to overcome these difficulties.

Up to now in the U.S. (and in most other countries), federal agencies have been the primary supporters of ocean observing activities, with some notable exceptions, e.g., the $4 million support of Deep Argo float deployments from the Paul G. Allen Philanthropies and some nonprofit funding for ocean conservation research and technological development. But few non-governmental organizations have provided funding to sustain long-term projects such as ocean observing activities. A partnership organization would build constituencies and provide a venue for identification of priority efforts to direct resources. Here we list some of these opportunities from working across sectors.

The international Ocean Partnership for Sustained Observations (OPSO) could play an important role in helping determine what programs and institutions are required for long-term observations. But to be successful it will have to do more than that. It will have to be active in establishing stronger coordination, identifying financial needs, and raising and finding funds for the necessary institutions and programs. The collaborative structure of the OPSO ensures that the representation is comprehensive and that activities will be done with full knowledge of existing institutions and programs.

While identification of coordinated uses for existing funding will be a significant step, there is also a role for a fund-raising focus, probably with a designated “Advancement” or “Development” office.

We have outlined above the needs for expanding ocean observations to a much wider group of users who are looking to the ocean for more resources from fish to mining and from generating clean energy to finding new genetic resources. Dealing with climate change, from warming to acidification, will require much better monitoring of life and physical properties of the ocean. The need for a broad approach means that ocean actors beyond national governments must be involved.

National Governments

There are two approaches to be considered here: first would be working with national governments that have demonstrated interest in expanding their ocean programs to meet national and global needs. Up to now, the U.S. has been the major financial supporter of *in-situ* and remote sensing ocean observations, but other nations also have strong programs. Expansion of ocean programs is happening in a number of countries, including for example, Germany and China, South Korea, Japan, and Indonesia. A direct approach to the ocean agencies in these countries would be the right way to start. Second would be to tackle the UN system, now recently focused on oceans working with the new UN Oceans interagency mechanism that is looking to enhance the coordination of the relevant UN bodies, of which there are many. A careful study of this new coordination could yield information about where in the system a long-term observation program might find traction (beyond UNESCO/IOC, already fully aware of the needs).

Philanthropies

Philanthropic efforts have in part filled gaps in institutional support for projects. The OPSO could follow up on the NASEM 2017 report, which suggests “synergistic coordination,” including asking foundations to perhaps offer guidance for structuring sustained observation programs. Here the leadership of the OPSO should work directly with the leaders of the philanthropies. For projects, the OPSO should identify a small number of people who could analyze which projects are currently active, and possibly identify where ocean observations could help meet foundation needs. The organization “Funding the Ocean.Org” (Funding the Ocean.org, 2018)[18] provides information and a map of where a number of foundations are funding projects, mostly focused on conservation issues.

Nonprofit, Non-governmental Organizations

The ocean observing community has much to offer the conservation community, showing how new technology can provide better and longer-term data to improve the success of conservation activities. It would be useful to start a dialog with organizations like World Wildlife Fund, Conservations International, Oceana, and the Nature Conservancy to see if they would like to collaboratively develop an approach for more comprehensive observations. The Nature Conservancy’s Ocean Wealth report gives many examples of where such a collaboration could begin (The Nature Conservancy, 2017).[19]

The Private Sector

Three aspects of engagement of the private sector through OPSO are through (1) collaboration with resource extraction companies to include observations as part of their practices, ranging from oil and gas exploration and operations to deep-sea mining activities, (2) coordinating on applications for new technologies and instruments, and (3) support from corporations using long-term ocean data and information to help their corporate products. Examples of the first are the desire of oil companies to find resources and to protect the ocean from spills and blowouts and the need to monitor possible deep-sea mining activities for the long-term. An example of the

[18]http://fundingtheocean.org/resources/
[19]http://maps.oceanwealth.org/

second is the rapidly growing autonomous vehicle industry led by the private sector but providing value for national needs (e.g., Saildrone). For the third, the logical group is the reinsurance companies whose forecasts rely partly on ocean data, as well as the private weather companies that are now getting into longer-range forecasting. The discussion needs to be how technology can help meet a bottom line, and help a company meet corporate sustainability commitments. There may be a good opportunity here for the OPSO to work specifically with the World Ocean Council (WOC) whose mission is to bring together the multi-sector Ocean Business Community to catalyze global leadership and collaboration in ocean sustainability and "Corporate Ocean Responsibility." The WOC provides responsible companies from the Ocean Business Community the ability to collectively address cross-cutting ocean sustainable development challenges and shape the future of the ocean by engaging and working with other ocean stakeholders.

NEXT STEPS

In short, we believe that more effective coordination will bring multiple constituencies together and motivate more strategic and potentially new funding. To that end, in this section we propose a series of next steps for developing a coordinated effort to bring a variety of potential stakeholders into an international collective impact organization that focuses on ocean observations. The section provides a summary of best practices in initiating collective impact organizations and suggestions on how the observations community might move forward with a collective impact approach. These next steps are not meant to be prescriptive of the organization's agenda and membership, but rather provides a guideline for how such an organization could begin.

Phases of Collective Impact

The steps outlined below are based on research documenting successful launching of a collective impact organization. Hanleybrown et al. (2012) outline three phases of development for collective impact organizations (**Figure 7**) and describe factors that enhance probability of success for these stages. These include an influential champion (or group of champions), adequate financial resources, and an urgency for change. All of these factors are present now, or could be, for enhancement of the ocean observing system. We note that these three phases need not proceed independently but will likely involve some iteration between different activities.

Establish a Group of Strong Supporters or Champions

The initial charge of this international group would be to develop a straw proposal of the group's agenda and scope (see section The Collective Impact Organization). The initial group should include representation from a diverse set of stakeholders. The group would ideally be coordinated by an established organization, to be determined by discussion, and should include initial high-profile partner organizations that are representative of the diverse set of potential contributors to the organization. The group should meet regularly to develop a proposed agenda and scope, and to identify relevant stakeholders for listening sessions.

The first step would be to identify interested individuals who represent a diverse set of interests who would be served by ocean observations, those who conduct them, and others as appropriate. One role of the initial group would be to identify who all needs to be at the table, and start contacting them to set up some initial meetings.

Mapping the Landscape Through Listening Sessions

Once an initial set of champions is convened, the group should set up listening sessions that identify and document needs of various communities. This also serves to map the landscape of the organization, and to better define boundaries for the agenda. These listening sessions might include "Town Hall" meetings at scientific conferences such as AGU, EGU, and AMS meetings, or ocean industry trade conferences and sustainable ocean meetings as well as direct contact with existing organizations related to the ocean observing system (GOOS, CLIVAR, organizational meetings for the Decade of Ocean Science 2021–2030, etc.).

Results from the listening sessions will provide information for the original group that will provide input on new members or changes to the agenda and scope. These listening sessions should also aim to identify a set of stakeholder advisors that will form an (or multiple) advisory committee to the collective impact organization.

Establish the Backbone Infrastructure

A critical component of collective impact organization is a backbone infrastructure that provides support for the activities of the wider effort. This backbone infrastructure provides a centralized support for the decentralized landscape of stakeholders involved in the organization. The support includes internal communication and coordination within the group (e.g., setting up meetings, coordinating communication, providing needed data), and outward communication and coordination (the initial listening sessions, and continued communication with relevant stakeholder communities.)

It is important to remember that the backbone infrastructure does not set the agenda or boundaries of the organization but is responsible for helping to carry out that agenda. The development of core infrastructure helps ensure that the program has a strong base.

Moving Forward to Future Modes of Support and Governance

The listening sessions proposed above could start with an initial workshop including, as noted above, representatives from the ocean science and meteorology community, the national and state governments, the private sector, foundations, and NGOs. To avoid an impossibly large meeting, two or three initial meetings might be considered. Examples of organizations that might be included are IOOS, CLIVAR, POGO, and maybe others from the ocean science community, and JCOMM for the ocean weather community; the World Ocean Council and the World Economic Forum for the private sector; the

Phases of Collective Impact

Components for Success	PHASE I Initiate Action	PHASE II Organize for Impact	PHASE III Sustain Action and Impact
Governance and Infrastructure	Identify champions and form cross-sector group	Create infrastructure (backbone and processes)	Facilitate and refine
Strategic Planning	Map the landscape and use data to make case	Create common agenda (goals and strategy)	Support implementation (alignment to goals and strategies)
Community Involvement	Facilitate community outreach	Engage community and build public will	Continue engagement and conduct advocacy
Evaluation and Improvement	Analyze baseline data to identify key issues and gaps	Establish shared metrics (indicators, measurement, and approach)	Collect, track, and report progress (process to learn and improve)

FIGURE 7 | From Hanleybrown et al. (2012), the phases of effort toward developing a collective impact organization.

foundations that have supported ocean observations (W. M. Keck Foundation, Paul G. Allen Philanthropies, etc.); and appropriate environmental organizations such as The Wildlife Conservation Society, Conservation International, and Oceana. This list is just indicative of the kinds of organizations that might be involved.

The purpose of this initial workshop would be to assess the level of interest from the various constituencies in developing a more formal arrangement. Funding for the initial activities of the collective impact organization could initially come from contributions from each of the parties involved.

Conclusion

The oceans, with 50 times as much carbon as the atmosphere, 1,000 times the heat capacity and 100,000 times as much water, clearly play a central role in the climate and habitability of planet Earth (Schmitt, 2018). In the end, society as a whole benefits from all the ways that comprehensive ocean observations contribute to economies and human well-being, including all of those nations, communities, and individuals who depend on ocean use and resources. From small island states to coastal nations to worldwide commerce and trading, an ocean whose resources are used sustainably provides a steady foundation for human health and wealth [see *Mapping Ocean Wealth* (The Nature Conservancy, 2017)].[19]

In the discussion above, we have outlined how the scope of ocean observations is changing and how new demands for ocean information are emerging with a wide variety of priorities and expectations. The way that oceanographers work is also changing, with an increase in decentralized efforts at tackling problems. But government funding for observations has remained flat. To achieve the required funding increases, we argue here for new, flexible and nimble organizations that capitalize on the collective interest in oceans.

The driver for all of this is sustainable use of the ocean and its resources, now a well-articulated UN goal. A network of long-term and comprehensive observations is required to meet that goal. Such a network of observations requires participation from all sectors of the ocean and atmosphere communities ranging from exploration to weather and climate forecasting to resource extraction. In the near term, one key opportunity lies in the plans of the United Nations for an ocean conference in 2020 to address protection of marine biodiversity in the high seas. Just as the 2015 Paris Climate Conference drew attention to climate change and resulted in key agreements, it is likely that the UN 2020 Oceans meeting could be a focal point for bringing attention to the need for comprehensive ocean observations.

An important part of the new international collective impact organization will be to bring in new users and new technology, helping to create a whole that is bigger than the sum of its parts, a nucleus that makes everyone more effective. We urge the ocean community to embrace this broader set of users to create a collective impact organization that will maximize the collaboration of ocean actors and to lay the foundation for continued and increased funding for the enhanced observations that are required.

MAKING OCEANOBS'19 A STEPPING-OFF MILESTONE

We propose that we begin work at OceanObs'19 toward a collective impact organization, the Ocean Partnership for Sustained Observations and that the immediate target is an initial workshop. The workshop could have two sessions, one a plenary with keynote presentations to galvanize and engage a diverse set of users of ocean observations. The second session would begin the work to develop the backbone organization and start progress toward the collective impact organization. Further milestones would be an initial meeting of the Ocean Partnership for Sustained Observations in 2020, potentially allowing a role in 2020 meetings such as the Conference of the Parties to the Convention on Biological Diversity and 2020 UN Climate Change Conference (COP 26). The Partnership would also seek a role in the UN Decade of Ocean Science for Sustainable Development (2021–2030).

A beginning is to coordinate existing efforts by bringing multiple constituencies together. By bringing together constituencies across different sectors, we can more clearly define problems that many constituencies face, that can be solved through collective coordination of observations. This can also motivate new funding via recognizing key problems.

The landscape is changing, creative new funding sources are emerging with a wide variety of priorities and expectations. The way that we do work is also changing, with the increase in decentralized efforts at tackling problems. We need to think about new, flexible organizations that capitalize on the collective interest in our oceans and in ocean observations. We need new, nimble organizations that interact with a wide range of stakeholders to produce a collective impact that is "more than the sum of the parts." We need engagement from private foundations, the private sector, and new constituencies that will benefit from sustained ocean observations. Coordination across many diverse groups will build a new, broader base of support. We have outlined our suggesting for such an effort herein. We propose an initial discussion at Ocean Obs'19.

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RW, DB, MG, SR, RS, ET, and DV: contributed to the drafting and revision of this paper.

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REFERENCES

Abbot, J., and Marohasy, J. (2012). Application of artificial neural networks to rainfall forecasting in Queensland, Australia. *Adv. Atmos. Sci.* 29, 717–730. doi: 10.1007/s00376-012-1259-9

Baker, D. J., Schmitt, R. W., and Wunsch, C. (2007). Endowments and new institutions for long-term observations. *Oceanography* 20, 10–14. doi: 10.5670/oceanog.2007.19

Bates, A. E., Helmuth, B., Burrows, M. T., Duncan, M. I., Garrabou, J., Guy-Haim, T., et al. (2018). Biologists ignore ocean weather at their peril. *Nature* 560, 299–301. doi: 10.1038/d41586-018-05869-5

Chiodi, A. M., and Harrison, D. E. (2017). Simulating ENSO SSTAs from TAO/TRITON winds: the imacts of 20 years of buoy observations in the Pacific waveguide and comparison with reanalysis products. *J. Clim.* 30, 1041–1059. doi: 10.1175/JCLI-D-15-0865.1

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2013). "Carbon and other biogeochemical cycles," in *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge; New York, NY: Cambridge University Press), 465–570.

ClimateWorks. (2008). *Design to Win: Philanthropy's Role in the Fight Against Global Warming*. San Francsico, CA.

Czaja, A., and Frankignoul, C. (1999). Influence of the North Atlantic SST on the atmospheric circulation. *Geophys. Res. Lett.* 26, 2969–2972. doi: 10.1029/1999GL900613

Enfield, D. B., Mestas-Nuñez, A. M., and Trimble, P. J. (2001). The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Lett.* 28, 2077–2080. doi: 10.1029/2000GL012745

Freeman, L., and Freeman, S. (2016). Rapidly obtained ecosystem indicators from coral reef soundscapes. *Mar. Ecol. Prog. Ser.* 561, 69–82. doi: 10.3354/meps11938

Hanleybrown, F., Kania, J., and Kramer, M. (2012). "Channeling change: making collective impact work," in *Stanford Social Innovation Review*. (Accessed January 26, 2012).

Hansen, B. K., Bekkevold, D., Clausen, L. W., and Nielsen, E. E. (2018). The sceptical optimist: Challenges and perspectives for the application of environmental DNA in marine fisheries. *Fish Fish.* 19, 751–768. doi: 10.1111/faf.12286

Hansen, J. W., Hodges, A. W., and Jones, J. W. (1998). ENSO influences on agriculture in the southeastern United States. *J. Clim.* 11, 404–411.

IOC-UNESCO (2017). *Global Ocean Science Report – The current status of Ocean Science Around the World.* eds L. Valdes et al. Paris: UNESCO Publishing.

Kania, J., and Kramer, M. (2011). "Collective Impact." in *Stanford Social Innovation Review* 9, 36–41.

Khan, M. I., Shin, J. H., and Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microb. Cell Fact.* 17:36. doi: 10.1186/s12934-018-0879-x

Kirono, D. G., Chiew, F. H., and Kent, D. M. (2010). Identification of best predictors for forecasting seasonal rainfall and runoff in Australia. *Hydrol. Process.* 24, 1237–1247. doi: 10.1002/hyp.7585

Li, L., Schmitt, R. W., Ummenhofer, C.C., and Karnauskas, K.B. (2016a). Implications of North Atlantic sea surface salinity for summer precipitation over the U.S. Midwest: mechanisms and predictive value. *J. Clim.* 29, 3143–3159. doi: 10.1175/JCLI-D-15-0520.1

Li, L., Schmitt, R. W., and Ummenhofer, C. C. (2018). The role of the subtropical North Atlantic water cycle in the 2015 extreme precipitation events in the US. *Clim. Dyn.* 50, 1291–1305. doi: 10.1007/s00382-017-3685-y

Li, L., Schmitt, R. W., Ummenhofer, C. C., and Karnauskas, K. B. (2016b). North Atlantic salinity as a predictor of Sahel precipitation. *Sci. Adv.* 2:e1501588. doi: 10.1126/sciadv.1501588

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., and Glover, L. K. (2012). *A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing*. Paris: UNESCO.

Lindstrom, E. J., Kendall, J. J. Jr., and Chicoski, B. (2009). Ten years of NOPP accomplishments. *Oceanography* 22, 25–27. doi: 10.5670/oceanog.2009.34

Liu, T., Schmitt, R. W., and Li, L. (2018). Global search for autumn-lead sea surface salinity predictors of winter precipitation in southwestern United States. *Geophys. Res. Lett.* 45, 8445–8454. doi: 10.1029/2018GL079293

Macreadie, P. I., Fowler, A. M., and Booth, D. J. (2011). Rigs-to-reefs: will the deep sea benefit from artificial habitat?. *Front. Ecol. Environ.* 9:455–461. doi: 10.1890/100112

Mahlstein, I., and Knutti, R. (2012). September Arctic sea ice predicted to disappear near 2°C global warming above present. *J. Geophys. Res.* 117:D06104. doi: 10.1029/2011JD016709

Namias, J. (1959). Recent seasonal interactions between North Pacific waters and the overlying atmospheric circulation. *J. Geophys. Res.* 64, 631–646. doi: 10.1029/JZ064i006p00631

Namias, J. (1978). Multiple causes of the North American abnormal winter 1976–77. *Mon. Weather Rev*. 106, 279–295. doi: 10.1175/1520-0493(1978)106<0279:MCOTNA>2.0.CO;2

National Academies of Sciences, Engineering, and Medicine (NASEM) (2016). *Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts*. Washington, DC: The National Academies Press.

National Academies of Sciences, Engineering, and Medicine (NASEM) (2017). *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate*. Washington, DC: The National Academies Press.

National Research Council (NRC). (2015). *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. Washington, DC: The National Academies Press.

NOAA (2015) *FY 2016 NOAA Budget Summary*. Available online at: https://www.corporateservices.noaa.gov/~nbo/fy16_bluebook/FY2016BudgetSummary-web.pdf (Accessed December 19, 2018).

NOAA (2018a). *What is Blue Carbon?* Available online at: https://oceanservice.noaa.gov/facts/bluecarbon.html (Accessed October 5, 2018).

NOAA (2018b) *FY 2019 NOAA Budget Summary*. Available online at: https://www.corporateservices.noaa.gov/nbo/fy19_bluebook/FY19-BlueBook.pdf (Accessed December 19, 2018).

NOAA Medicines. (2018). Available online at: https://oceantoday.noaa.gov/medicinesfromthesea/ (accessed October 5, 2018).

Ocean US (2002). *Building Consensus: Toward an Integrated and Sustained Ocean Observing System (IOOS).*Arlington, VA: Ocean.US, 175.

OECD (2016). *The Ocean Economy in 2030.* Paris: OECD Publishing.

Palmer, T. N., and Zhaobo, S. (1985). A modelling and observational study of the relationship between sea surface temperature in the north-west Atlantic and the atmospheric general circulation. *Q. J. Roy. Meteorol. Soc*. 111, 947–975. doi: 10.1002/qj.49711147003

POGO (Partnership for Observation of the Global Oceans). (2018). *POGO Training and Education*. Available online at http://www.ocean-partners.org/training-education (accessed December 17, 2018).

Rammel, C., Stagl, S., and Wilfining, H. (2007). Managing complex adaptive systems — A co-evolutionary perspective on natural resource management. *Ecol. Econ.* 63, 9–21. doi: 10.1016/j.ecolecon.2006.12.014

Rhein, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Feely, R. A., et al. (2013). "Observations: ocean," in *Climate change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge; New York, NY: Cambridge University Press), 255–316.

Roberts, J., and Ali, A. (2016). *The Blue Economy and Small States, Commonwealth Blue Economy Series, No. 1*. London: Commonwealth Secretariat.

Schmitt, R. W. (2018). The ocean's role in climate. *Oceanography* 31, 32–40. doi: 10.5670/oceanog.2018.225

Stommel, H. (1989). Why we are oceanographers. *Oceanography* 2, 48–54.

Stone, G. S., and Degnarian, N. (2017). "The soul of the sea in the age of the algorithm," in *Sedgwick,* Maine: Leete's Island Books/World Ocean Observatory, 189.

Turner, S., Merchant, K., Kania, J., and Martin, E. (2012). "Undertsanding the value of backbone organizations in collective impact: Part1," in *Stanford Social Innovation Review.* (Accessed July 17, 2012).

Ummenhofer, C. C., Sen Gupta, A., Pook, M. J. and England, M. H. (2008). Anomalous rainfall over southwest Western Australia forced by Indian Ocean sea surface temperatures. *J. Clim*. 21, 5113–5134. doi: 10.1175/2008JCLI2227.1

Ummenhofer, C. C., Sen Gupta, A., Taschetto, A. S. and England, M. H. (2009). Modulation of Australian precipitation by meridional gradients in east Indian Ocean sea surface temperature. *J. Clim.* 22, 5597–5610. doi: 10.1175/2009JCLI3021.1

Van Parijs, S. M., Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., et al. (2009). Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Mar. Ecol. Prog. Ser.* 395, 21–36. doi: 10.3354/meps08123

Watkins, J. L., and Brierley, A. S. (2002). Verification of acoustic techniques used to identify Antarctic krill. *ICES J. Mar. Sci.* 59, 1326–1336. doi: 10.1006/jmsc.2002.130

Wunsch, C., Schmitt, R. W., and Baker, D. J. (2013). Climate change as an intergenerational problem. *Proc. Natl. Acad. Sci. U.S.A*. 110, 4435–4436. doi: 10.1073/pnas.1302536110

Yamamoto, S., Masuda, R., Sato, Y., Sado, T., Araki, H., Kondoh, M., et al. (2017). Environmental DNA metabarcoding reveals local fish communities in a species-rich coastal sea. *Sci. Rep.* 7:40368. doi: 10.1038/srep40368

Yang, Z., and Copping, A.E. (2017). *Marine Renewable Energy: Resource Characterization and Physical Effects.* Cham: Springer International Publishing.

Zhu, Y., Zhou, X., Peña, M., Li, W., Melhauser, C. and Hou, D. (2017). Impact of sea surface temperature forcing on weeks 3 and 4 forecast skill in the NCEP Global Ensemble Forecasting System. *Weather and Forecast*. 32, 2159–2174. doi: 10.1175/WAF-D-17-0093.1

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