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Introduction to The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and the Seabed 2030 Initiative

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Introduction to The United Nations Decade of Ocean Science for Sustainable Development (2021 – 2030) and the Seabed 2030 Initiative

Guest Editors: Donna M. Kocak and Liesl Hotaling

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2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

Introduction to The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and the Seabed 2030 Initiative

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Imagine a clean and healthy ocean, free of plastics and other pollution, supporting an abundance of flora and fauna. Long-term, decadal observations collected across the vast expanse of the ocean—from one horizon to the next, down to the deepest trenches, and all spaces in between—assist us in tracking, predicting, managing, and adapting to changes in the marine environment. Our global "new blue economy" thrives from the energy, food, medicine, transportation, and recreational activities supported by a sustainably utilized ocean. In addition to using these ocean resources, people around the world are fully aware of the role the ocean plays in our daily lives. The United Nations (UN) shared this vision and declared 2021–2030 the United Nations Decade of Ocean Science for Sustainable Development (a.k.a. "the Ocean Decade"). The Ocean Decade is a call to action with the motto of "the science we need for the ocean we want." The UN is effectively challenging humanity to "integrate new societal needs and encourage new partnerships among oceanographers working in different disciplines leading to new discoveries about the ocean's role in climate regulation and coastal ocean processes," while supporting business operations including shipping, energy, fishing, and aquaculture.

This special issue of the *Marine Technology Society Journal* (*MTSJ*) is the first in a multi-volume series that will span the next 10 years. For the first time, we are offering this as an open-access issue to increase awareness of the Ocean Decade with the larger ocean community. In addition, we have opened the *MTSJ* archives to allow access to content 12 months and older with no membership required. We invite you to explore these treasured archives and hope that you will consider contributing as an author or guest editor to a future issue.

Included in this issue is a description of the goals, objectives, and initiatives that have thus far been announced by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). Dr. Vladimir Ryabinin, Executive Secretary of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, kicks off this issue with an overview of the Ocean Decade that includes a discussion of why the timing is so critical and ways that we all can contribute. This is followed by commentaries from three of the Ocean Decade's partnering organizations and the roles these organizations will play: Global Ocean Observing System (GOOS), International Hydrographic Organization (IHO), and the Marine Technology Society (MTS).

Next up is a discussion of one of the most ambitious initiatives in oceanographic history, The Nippon Foundation-GEBCO Seabed 2030 Project, which aims to map 100% of the ocean floor by 2030. The Seabed 2030 Project Director Jamie McMichael-Phillips describes the project and its goals over the next 10 years, which coincide with the Ocean Decade. The next commentary by David Millar of Fugro discusses some technological innovations in mapping that will help support the Seabed 2030 Project and the goals of the Ocean Decade.

Submissions from our MTS India Section members follow an Ocean Decade objective to focus on initiatives and ocean technologies by ocean scientists and technologists in India. Dr. Ramasamy Venkatesan et al. discuss technological trends and the significance of essential ocean variables collected by moored observatories; and Sujith Kumar et al. describe a Web-GIS and mobile-based application to enhance safety to the fishing community.

The remaining submissions discuss inspiring U.S. contributions to the Ocean Decade. The U.S. National Committee (USNC) challenged the community to think boldly and creatively about ways to advance marine science in support of sustainable development. With this in mind, the Committee issued a call for "Ocean-Shots: ambitious, transformational research concepts that draw inspiration and expertise from multiple disciplines and fundamentally advance ocean science for sustainable development." In response to this call, we are pleased to share 43 of these ideas with our readers in this issue.

We hope you enjoy this introduction to the Ocean Decade and that you will continue to follow future issues in this series as we share the scientific and technological advancements moving us all closer to the ocean we want.

COMMENTARY

The Ocean Decade: A Revolution in How We Generate and Use Ocean Science

AUTHOR
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Executive Secretary,
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The global ocean community is generating major advances in ocean science. Disruptive technological innovations and groundbreaking large-scale initiatives are changing the ways we study the ocean. The true economic potential of the ocean is largely untapped and investments in ocean science and technology could unleash about US$3 trillion by 2030, multiply six-fold the amount of seafood available and generate 40 times more renewable energy, creating many new employment opportunities. Most importantly, these developments are achievable in a sustainable manner, in stark contrast to what we currently observe in the ocean. Indeed, we are intimately aware of the alarming trends and overwhelming evidence from the equator to the poles that rising sea level, extreme weather events, ocean acidification, deoxygenation, pollution, and many other stressors are disrupting marine ecosystems and threatening all life on this planet as we know it. As leaders on the frontiers of ocean science, we have a shared responsibility to make sure this does not continue to happen, and that the world makes choices for a healthier and more sustainable ocean economy.

Why a Decade of Ocean Science?

With most governments spending less than 2% of their research budgets on ocean science, one of the first barriers we must overcome is ensuring that more funding is targeted at stimulating ocean research. Second, we must also acknowledge that past research efforts have largely focused on delivering the "science we want." This may be useful for diagnosing problems, but this is not very useful for offering solutions to solve the many complex problems the ocean faces so future generations can keep benefitting from its resources.

This is where the UN Decade of Ocean Science for Sustainable Development, 2021–2030 (the "Ocean Decade"), comes in. The solutions-oriented nature of the Ocean Decade creates conditions for a key transformation in the way we generate and use ocean science, both quantitative and qualitative, so we can move towards the Ocean Decade's vision of the "science we need for the ocean we want." The solutions will be diverse and could include new policies, management frameworks, innovations or technologies, training materials and more—all based on scientific data and knowledge. The scale of this initiative is unprecedented, but it could not happen at a more critical time, especially against the current backdrop of the global COVID-19 pandemic and accelerating climate change.

IOC's Role in the UN Ocean Decade

The Intergovernmental Oceanographic Commission (IOC) of UNESCO is fully committed to coordinate and serve as a global unifier for this ambitious decadal endeavor. Having celebrated its 60-year anniversary in December 2020, it has a long history as the leading UN body for ocean science and services. Over the next 10 years, the IOC will leverage and build on past experiences and partnerships, so that the Decade can deliver on its mission and "catalyze transformative and tangible ocean science solutions for sustainable development, reconnecting people to our ocean." One key factor of progress will the consolidation of the whole value chain of ocean science that begins with ocean observations, generation of data, modelling, and analysis, resulting in ocean services, for example, for tsunami warnings and assessments as well as acting at the science-policy interface and developing capacity for all. We need to turn the practical side of the ocean science into an end-to-end system to be able to effectively support sustainability.

How Will the Work of the Ocean Decade Be Coordinated?

The Ocean Decade is structured in a way that will harness, stimulate, and coordinate research efforts at all levels to support the delivery of information, action, and solutions needed to achieve the 2030 Agenda. The IOC will coordinate the overall work of the Decade at the global level and support stakeholders as they collectively align efforts to co-design and co-deliver a Decade of Ocean Science. This effort will be further supported by decentralized bodies around the world hosted by other UN agencies or governments, international and regional organizations, or by other partners. A Decade Advisory Board will be established to provide strategic advice to the IOC on implementing the Ocean Decade. Please stay tuned, nominations for membership will be opening during the second half of 2021.

What Will Guide the Ocean Decade?

The work of the Ocean Decade will be guided by the Implementation Plan. This document, which was carefully and meticulously prepared over the last few years, with invaluable input from the global ocean community, is the living roadmap we will follow to achieve the Ocean Decade's vision. This Plan provides information on how stakeholders can participate, how resources will be mobilized, how efforts will be promoted and coordinated, and how impact will be measured throughout the Decade.

The Implementation Plan is structured in a way that will allow us to build on existing achievements and deliver action across all geographies, sectors, disciplines, and generations. As shown in Figure 1, this includes addressing the seven desired Decade Outcomes that describe the "ocean we want" at the end of the 10 years (or, better, earlier), and delivering on 10 Decade Challenges—the most immediate and pressing priorities of the Decade.

The "Knowledge and Solutions Challenges" focus on scientific research priorities in social, economic, and political science disciplines as well as indigenous and local knowledge. The "Essential Infrastructure Challenges" center on ocean observations and data. And the "Foundational Challenges" focus on essential, cross-cutting elements of the enabling environment for the Ocean Decade, making sure that no one is left behind and that the Decade leads to a positive change in human relations with the ocean. Together, these complementary aspects will guide the design and implementation of different Decade Actions by diverse partners and stakeholders.

How Will the Ocean Decade Achieve the "Ocean We Want"?

Throughout the Decade, initiatives will flourish and grow, building scientific capacity so we can effectively conserve and protect the ocean. In this spirit, we will be organizing a wide range of activities, events, and regular Calls for Action to bring different ocean stakeholders together so they can co-design and co-deliver specific solutions or actions. Actions can manifest differently but will generally be in the form of programs (large-scale, multi-year, and multi-country initiatives), projects (shorter and more focused initiatives), as well as activities (events, publications, exhibitions, workshops, conferences, or training opportunities), and/or contributions of financial and/or in-kind resources. Actions must meet specific endorsement criteria before being officially recognized as part of the collective effort to meet the Ocean Decade's vision and mission. IOC recently closed our first Call for Actions but will be holding regular calls over the Decade.

FIGURE 1

Check out our Implementation Plan in 6 languages: Full Version and Summary.

What Kind of Science Do We Need for the "Ocean We Want"?

We will only achieve the "ocean we want" if the Ocean Decade generates knowledge and exchanges state-of-the-art technologies and capacity that respond to the needs of users around the world. Some emerging developments that could help combat some of the world's biggest ocean challenges and contribute, therefore, to the vision and mission of the Decade include:

- Interdisciplinary research on ocean connectivity (across physics, chemistry, biology, ecology, and human activities) with a focus on conservation and sustainable use of the ocean.
- Integration of emerging technologies such as artificial intelligence and machine learning into data collection, management, analysis, and applications.
- Innovative technologies that can help us tackle accumulating pollution in the environment (e.g., but not only plastics and microplastics), adapt or restore declining coral reefs, and guarantee sustainability in exploitation of ocean resources.
- Improved knowledge, approaches, and tools that support the recovery of wild fish stocks, sustainable fisheries management practices, and sustainable expansion of aquaculture.
- Increased knowledge and support to innovation, technological development and decision-support tools that address priority needs for energy production, tourism, transport, and pharmaceutical industries.
- Better practices for retrieving data from ocean observing networks, essential for improving weather and climate services, ocean forecasting and services, tsunami warning, and climate change studies.

Who Can Participate?

The Ocean Decade is everyone's Decade, so anyone can participate, and everyone has a role to play no matter how big or small is the contribution. The Ocean Decade transcends all ages, genders, cultures, sectors and disciplines—so it is not just about the natural and social scientists, but also actors from all sectors within government, industry, philanthropy, local and indigenous communities. For it to succeed, it is crucial that knowledge generators and users collaborate outside their traditional communities in an iterative process of co-design and co-delivery of ocean science. We also strongly encourage early-career ocean professionals to get involved and lead the charge so that the Decade lives beyond 2030!

Why Should You Participate?

Getting involved will bring many benefits. Foremost, imagine the positive energy being part of a highly visible, shared, global effort that builds on decades of achievement in ocean science and helps us shape a sustainable future for our ocean. Besides this, becoming part of this effort to change the way we generate and use ocean science has great potential to lead to new partnerships, capacity building and technology transfer, spur emerging businesses, stimulate innovations, offer cost savings, create improved access to markets, mobilize investments in R&D, and so much more!

How Can You Participate?

There are many different ways to participate or contribute to the Ocean Decade; for example:

- Show leadership by committing to the vision and mission of the Ocean Decade.
- Incorporate one or more of the Decade Challenges, Objectives, or Outcomes in your work.
- Search for new partners and join activities where you can contribute, leverage, and accelerate efforts.
- Reach out across geographies and across sectors to initiate or participate in the Co-Design and Co-Delivery of one or more Decade Actions.
- Send us an expression of interest to become a Decade Implementing Partner and support coordination and implementation of the Ocean Decade.
- If you are a resource provider, join the Decade Alliance, which will provide a highly visible platform that aims to catalyze large-scale resource commitments toward the Decade through networking, resource mobilization, and influence.
- Apply to become a member of the Decade Advisory Board, which will provide strategic oversight on how we implement the Ocean Decade. Nominations for membership will open during the second half of 2021.
- Give early-career ocean professionals in your team opportunities to attend and participate in Ocean Decade efforts.
- Spread the word about the Decade, follow activities, participate in dialogues and events, join the Global Stakeholder Forum to be launched in late 2021, check out our website, or contact us to find out more!

Conclusions

The Ocean Decade is a once-in-a-lifetime opportunity to create a robust enabling environment that brings generators and users of ocean science together so that the knowledge generated supports a sustainable ocean economy. But we will only succeed if we manage to multiply the innovative potential of industry with the transformative power of ocean science. I hope this commentary could inspire readers to join the Decade movement and become part of this ocean knowledge revolution, co-creating the science we need for the ocean we want!

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COMMENTARY

The Global Ocean Observing System in the Ocean Decade: Transformation for Sustainable Development

AUTHOR

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Intergovernmental Oceanographic Commission of UNESCO–Global Ocean Observing System (GOOS)

The Ocean Decade outcomes of a healthy and resilient ocean, a productive ocean, a predicted ocean, a safe ocean, and a clean ocean will all rely on fit-for-purpose observations flowing from an integrated observing system, connected to prediction, assessment, science, and information services, that can deliver information to those who need it. Global Ocean Observing System observations are the foundation of much of the exciting work the Ocean Decade will carry out and essential to help give us the ocean we need for the future we want.

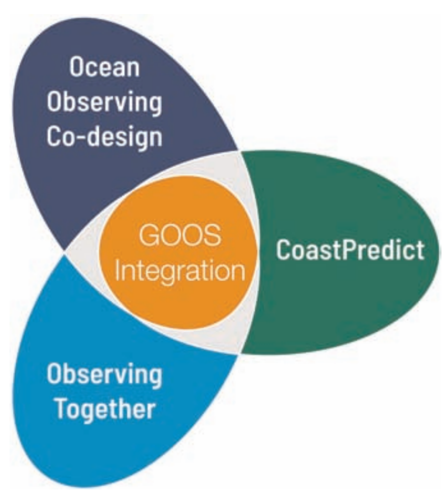
Today, observations provide the backbone for ocean and weather forecasts, deliver understanding of the ocean's role in the global climate system, as well as the climate's impact on the ocean. Long-term ocean observations allow us to better understand climate change and variability, and improve our forecasting of climate, weather, ocean status, and environmental hazards and their impacts. Achieving sustainability at global, regional, and local scales will require a comprehensive understanding of the current and projected state of our ocean, seas, and coasts across interlinked physical, biogeochemical, and biological realms.

Ocean information provides an evidence base for real-time decision making, tracking the effectiveness of management actions, and guiding adaptive responses on the pathway to sustainable development. Enhancing our ability to provide relevant information is vital to addressing societal needs, building resilience and climate adaptation strategies, as well as being the foundation for sustained and vibrant marine ecosystems. Ocean knowledge and information have the power to generate jobs and profits in a sustainable marine economy. By 2030, the ocean economy is predicted to be a much larger component of many national economies.[1]

The Ocean Decade will provide a "once-in-a-lifetime" opportunity for nations, industry, government, and science to work together to generate the global ocean science needed to support the sustainable development of our shared ocean.

Launching the Ocean Decade has made Global Ocean Observing System (GOOS)'s work more important than it has ever been. GOOS has identified three key areas for action that encapsulate the transformation needed. These GOOS Programs—Ocean Observing Co-Design, CoastPredict, and Observing Together—are the first programs of many that will actively drive the Ocean Decade.

- **Ocean Observing Co-Design:** Supporting the Decade of Ocean Science for Sustainable Development by transforming our ocean observing system assessment and design process.
- **CoastPredict:** Supporting the Decade of Ocean Science for Sustainable Development by revolutionizing global coastal ocean observation and forecasting and offering open and free access to coastal information.
- **Observing Together:** Supporting the Decade of Ocean Science for Sustainable Development by connecting ocean observers and the communities they serve.



[1]OECD publication, The Ocean Economy in 2030.

Ocean Observing Co-Design

Ocean Observing Co-Design will create a system co-designed with observing, modeling, and key user stakeholders that will evolve ocean observing and give us the ocean we need for the future we want.

The Challenge

Achieving the aims of the Ocean Decade demands readily available, fit-for-purpose ocean information. But much of the current ocean observing system has been built focusing on scientific and technical capability and attempting to join programs together. Rather than setting priorities based on what will give the most benefit for cost, scientists have been encouraged to compete with each other.

The Solution

Ocean Observing Co-Design will develop a well-designed, user-focused, and driven co-design process to create a truly integrated, agile system. It will work with existing and new observing networks, and integrate closely with the modeling community across assessment, assimilation, and prediction. Together, through partnership, we will build the process, infrastructure, and tools for ocean observing co-design necessary to support the Ocean Decade.

The Benefit

We will be able to:

- Better track the current state and future variability of the ocean.
- Predict and warn more skillfully.
- Manage ocean resources.
- Empower society to adapt to change.
- Assess the impact of action toward a sustainable ocean.

Ocean Observing Co-Design Objectives

1. *Integrate observing and modeling to measurably better support a sustainable ocean and society by focusing on measures ranging from stakeholder surveys to estimating the economic value of an improved prediction.*
2. *Make ocean observing and information appreciably more impactful through transformative co-design, working with the modeling community and key user stakeholders to achieve tangible integration and interoperability.*
3. *Develop system diagnostics, tools and reporting capability to better assess fitness-for-purpose across evolving requirements and use-inspired needs, including digital scenario tools that work backwards from intended impact to give us a priority plan for observing.*
4. *Establish the international capacity and modular infrastructure to co-design and regularly evaluate the observing system at different scales. For example, using a toolkit of software and user engagement/co-design methods that we can apply to global problems or local challenges such as keeping corals healthy for the economy.*
5. *Entrain new observing and information technology across all elements of the program. This would include platforms like autonomous robots with sensors, AI technology that can increase measurements at critical times, and new capabilities for existing platforms.*

CoastPredict

CoastPredict will redefine the science of observing and predicting the Global Coastal Ocean to help the Ocean Decade succeed in its aims and give us the ocean we need for the future we want.

The Challenge

Reducing risks and improving lives requires us to understand the coastal natural system as well as respond to ways in which climate change is affecting coastal populations. With increasing coastal urbanization, cities, and megacities, there is a greater need for advanced monitoring and predictions of extreme events such as flooding as well as pollution, habitat health, and other hazards.

The Solution

CoastPredict is a co-designed transformative response to science and societal needs. The Global Coastal Ocean concept at the center of CoastPredict considers all coastal ocean regions as an interface area. Atmosphere, land, ice, hydrology, coastal ecosystems, open ocean, and humans interact on a multiplicity of space and time scales that need to be resolved with proper scientific methods and consideration of uncertainties. A coastal focus will engage island nations and indigenous or local people, inspire early career ocean professionals, and be embraced by the general public.

The Benefit

We will be able to:

- Offer reliable predictions of different potential futures.

- Upgrade the data exchange infrastructure.
- Develop new multi-platform observing and modeling technologies.
- Improve human interaction with our oceans.
- Mitigate the impact of greenhouse gas emissions, restore habitats, and advance sustainable and blue economies.

CoastPredict Objectives

1. *A predicted Global Coastal Ocean.*
2. *A fit-for-purpose oceanographic information infrastructure benefiting stakeholders such as specialized users who interpret, share, and sometimes sell information to end users such as businesses, government, and individuals.*
3. *An integrated coastal ocean observing and forecasting system adhering to best practices and standards, designed as a global framework and implemented locally.*
4. *Open and free access to coastal information and the growth of ocean literacy.*
5. *Innovative and sustainable applications for coastal solutions/services including satellite and in-situ observations that directly benefit local populations and also covering ecosystem services such as food provision, well-being, and human health.*

Observing Together

Observing Together will transform ocean data access and availability by connecting ocean observers and the communities they serve through enhanced support to both new and existing community-scale projects. It will help give us the ocean we need for the future we want.

The Challenge

Today, many communities around the world are unable to access ocean data in a way that is truly useful and enables them to make informed decisions. They can struggle to see the value of investing in ocean observation.

The Solution

Observing Together aims to transform ocean data access and availability by connecting ocean observers and the communities they serve through enhanced support to both new and existing community-scale projects. It will leverage the GOOS's network of expertise to bring needed observations and forecasts to community users and into global data streams, making every observation count. For example, in the Pacific Island countries and territories 90% of Pacific Islanders live within 10 km of the coast and most economic activities rely upon the ocean—from commercial and sustenance fishing to surfing and dive tourism. Accurate ocean information and forecasts are critical for planning, safety at sea, and disaster mitigation along the coast, but oceanographic and marine forecasting expertise in the region is limited. Here, work carried out in partnership will include identifying ocean information user priorities, deploying new in-situ ocean observing equipment, and developing and delivering tools and training. When community users become aware of the real value of ocean observing and the data it produces to their lives, support for ocean science will grow. Through global connection, successful projects and approaches can be adopted by other communities.

The Benefit

We will be able to:

- Connect ocean observers and the communities they serve.
- Share ocean observations more widely.
- Go further to make every observation count.
- Develop new equipment and training programmes.
- Empower stakeholder communities.

Observing Together Objectives

1. *Equitable and practical access to ocean observations enabled by engagement and co-design with local observation and stakeholder communities.*
2. *A truly GOOS that makes a greater number of global and local observations available, integrated, interoperable, and comparable.*
3. *Strengthened connections, mutual understanding, and improved knowledge sharing between ocean observers and the stakeholder communities they serve, globally and locally.*
4. *Increased evidence that ocean observations are applied to solve problems and inform decision making at community, national, regional, and global levels.*
5. *Efficient design and use of ocean observations to maximize return on investment.*

Working Together to Achieve the Ocean Decade

There has already been a positive impact from the Ocean Decade in galvanizing the community to look at long-term goals and form the partnerships that will be needed to reach them. There are many partner actions, beyond ocean observations, that will have strong links to the three GOOS Programmes. For example the ForeSea Programme from Ocean Predict, where modeling and observational objectives are supported, the Digital Twins of the Ocean, which will enable users to explore and understand the consequences of specific interventions within a digital ocean, and Marine Life 2030 in the biological realm. There are also many exciting actions dedicated to closing specific gaps in the observing and forecasting system that will interact with the three GOOS Programmes; for example, OASIS, focused around improving air-sea flux monitoring; BOON, focused around genetic monitoring; ODYSSEY, focused around enabling new citizen science contributors from boats and divers; OneArgo, focused on expanding biogeochemistry, deep and high latitude monitoring with Argo floats; MegaMove, focused on using animal tracks and behavior for spatial management and conservation; and GO-SHIP Evolve, focused on developing sustained research vessel biological and ecosystem monitoring.

Supporting GOOS is one of the best possible ways to accelerate the work of the Ocean Decade to help make sure it achieves its aims and give us the ocean we need for the future we want.

For example:

- Our integrated nature covering multiple disciplines will help us disentangle and understand the cumulative impact of stressors on ecosystems.
- Assimilating ocean observations to boost the accuracy of model climate scenarios will indicate if local limits to coastal adaptation are years or decades away, guiding potentially costly investment.
- The knowledge we generate, the innovation we support, and the solutions we develop will optimize the role of the ocean in sustainably feeding the world's population under changing environmental, social, and climate conditions.

The need for expansion to a GOOS, designed to meet the requirements of a broader suite of users, is clear and urgent and was outlined in the Global Ocean Observing System 2030 Strategy.[2] It also identified that GOOS cannot achieve this vision alone, and that it will take partnership to grow an integrated, responsive, and sustained observing system.

GOOS will be the vehicle for designing, building, and widening the use of the necessary observations and information systems with capability enhanced by new lower-cost technologies.

The base for this investment has to be broad—encompassing philanthropy, governments, NGOs, and industry. With the establishment of National Decade Committees or Coordination Centers, there are promising signs that many nations are taking the challenge of the Ocean Decade seriously, and understand that strategic investment, now, across Ocean Decade actions, can have a major impact on human and ocean well-being. The outcomes for ocean and society are not disconnected, and the Ocean Decade offers a wealth of initiatives for long-term beneficial change. Careful investment will reap big rewards for society.

[2]The Global Ocean Observing System 2030 Strategy. IOC, Paris, 2019, IOC Brochure 2019-5 (IOC/BRO/2019/5 rev.) - www.goosocean.org/2030Strategy (https://www.goosocean.org/index.php?option=com_oetask=viewDocumentRecorddocID=24590).

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IHO's Role in the Ocean Decade

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ABSTRACT

The International Hydrographic Organization (IHO) is the intergovernmental international organization whose principal aim is to ensure that all the world's oceans, seas, and navigable waters are properly surveyed and charted. The commentary illustrates these and other IHO work items that are relevant to meet the major objectives of the Ocean Decade.

The International Hydrographic Organization (IHO) is the intergovernmental international organization whose principal aim is to ensure that all the world's oceans, seas, and navigable waters are properly surveyed and charted. The work is done by bringing together the national hydrographic agencies responsible for the conduct of hydrographic surveys, the production of nautical charts and related publications, and the distribution of Maritime Safety Information in accordance with the requirement set out in the International Convention for the Safety of Life at Sea (SOLAS) and other international regulations. The IHO has been hosted by the Government of Monaco since its creation in 1921 and its current membership stands at 94 Member States, which are represented by their respective national hydrographic offices (HOs).

IHO's Strategic Actions in Support the Ocean Decade

HOs everywhere are facing significant and rapidly developing challenges. The pace of technological innovations, from sensors to digital services, is increasing, bolstering the need for continuous adaptation of training and standards, thus requiring strong effort from HOs in investment and training. This is particularly significant for the automation of sensors carrying devices, and for new processing techniques from the field of artificial intelligence, which make it possible to handle "big data" and augment the capacity of human teams.

More generally, the crucial role of data and information in our societies entails important consequences on public policy (e.g., open data), the need for data assurance, including cyber security, all along the value chain, and on the involvement of the private sector, which are likely to have an impact on how investments in hydrography are sustained and how standards are developed.

Although safety of navigation remains a major driver for the IHO, hydrographic products and services are meant to support all activities associated with the oceans, seas, and navigable waters. As every human activity conducted in, on, or under the sea depends on knowing the depth and the nature of the seafloor and an understanding of the tides and the currents, hydrography is an essential foundation to the development of the Blue Economy. Yet, mankind has higher resolution maps of the Moon, Venus, and Mars than for most of the seas and oceans. This has a significant impact on what mankind can do at sea today in a safe, economical, and sustainable way. It is impeding progress and economic development in many, if not most, coastal states and has a major impact on the effective management, sustainable exploitation, and well-informed governance of the seas and oceans. It is this lack of knowledge that motivates IHO to become a relevant stakeholder helping to "facilitate a paradigm shift in the design and delivery of qualitative and quantitative ocean knowledge to inform solutions that will contribute to the 2030 Agenda for Sustainable Development."

There is a growing acknowledgement and awareness of the relevance and the underpinning contribution that hydrographic information can make in the context of the 2030 Agenda for Sustainable Development and in particular in support of its Sustainable Development Goal 14 –*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*. Consequently, many of IHO's work items are relevant to meet the three major objectives of the Ocean Decade:

Objective 1: Identify Required Knowledge for Sustainable Development, and Increase the Capacity of Ocean Science to Deliver Needed Ocean Data and Information

Hydrography as the branch of applied science that deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes and rivers, as well as with the prediction of their change over time, focuses on engineered solutions in support of the ocean decade objectives. To give an example, the enhancement and expansion of observation infrastructure is dependent on the swift transfer of new observation technology into regular, standardized, systematic, and repeatable operations. This is the core competence of HOs under their respective national responsibilities. The IHO as intergovernmental organization assists the implementation of such measures through technical standardization, the facilitation of interregional cooperation, and the coordination of capacity-building activities. A typical action to promote new technology is the campaign to designate hydrography as an enabler for autonomous technologies: firstly, for the conduct of hydrographic survey itself by means of autonomously acting sensor carriers such as autonomous surface vehicles, autonomous underwater vehicles, and flying drones with Lidar equipment. Secondly, to pave the way for the expected development of safe, secure, and environmentally sound Maritime Autonomous Surface Ships operations under the auspices of the International Maritime Organization (IMO), which will definitely rely on certified hydrographic information.

On a global scale, HOs operate the greatest fleet and maintain the widest range of fixed and floating infrastructure to undertake regular ocean observations under the specific aspect of their duties. Though hydrography is mainly regarded to be focused on sea survey and sea cartography, this discipline is in no way limited to those functions. Important physical marine systems like tides and water column observations and forecast are maintained thanks to the measuring infrastructure of HOs. Shallow water bathymetry takes advantage of the smart processing of satellite imagery and satellite altimetry conducted from space, which provides the main source for the so far unsurveyed parts of the oceans.

But the interpretation of hydrography as "to measure all the physics of the seas" leaves room for further expansion and offers opportunities for new forms of collaboration with ocean sciences. An excellent example is the capability of modern multibeam echo sounder systems to record, display, and log backscattered signals from the water column (WCI = water column imaging) in addition to the echoes from the seafloor. This extra information can deliver interesting insights into marine life in the upper water layers but it produces a huge amount of data, which requires tremendous time and effort for processing and interpretation. To tackle this, ocean scientists are called upon to develop smart technics to convert data into images and applying available image processing techniques. In turn, this backscatter processing may become a regular element of any modern acoustic survey. Another future field of mutual benefit for the hydrographic and the oceanographic domain could be the monitoring of micro plastic. If marine research manages the development of effective through flow sensors for micro plastic pollution, the hydrographic survey and observation infrastructure should be the suitable carrier and their experienced operators should be the best ones to carry out such monitoring systematically and repeatedly to create a comprehensive image of the global pollution situation and the effects in combat.

Objective 2: Build Capacity and Generate Comprehensive Knowledge and Understanding of the Ocean Including Human Interactions, and Interactions with the Atmosphere, Cryosphere, and the Land–Sea Interface

IHO standards and guidelines, intended to assist coastal states meet their obligations and requirements, fall under three main themes:

- nautical charts, issued on paper or in digital format (Electronic Navigational Charts), which are produced by national HOs to support safe navigation in accordance with the requirements of SOLAS;
- the maritime component of spatial data infrastructures being developed at the national and regional levels, which includes in particular high-resolution bathymetry (depth data) compiled by national HOs; and
- the global reference bathymetric data sets developed and made available through the GEBCO project (General Bathymetric Chart of the Oceans) operated jointly by the IHO and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

The GEBCO project is a joint program that is executed under the governance of the IHO and the IOC of UNESCO.

The GEBCO program produces and makes available a range of bathymetric data sets and products, including the GEBCO Gazetteer of Undersea Feature Names; the

GEBCO world map; GEBCO Cook Book; Web Map Services, and its lead bathymetric product: a global gridded bathymetric data set.

A significant source of data for these products is the IHO Data Centre for Digital Bathymetry (DCDB). One of the primary objectives of the IHO DCDB is to provide an authoritative source of bathymetry for ocean mapping requirements. In order to achieve this, GEBCO proactively collects, stores, and disseminates bathymetric data for the world's oceans. GEBCO has worked towards improving its participation in regional mapping activities and has appointed representatives to participate in selected meetings of the 15 Regional Hydrographic Commissions that operate under the umbrella of the IHO. Traditionally, GEBCO has focused on waters deeper than about 200 m; however, it is now actively collecting data in shallow water areas to support activities such as coastal zone management and development, and the mitigation of marine disasters such as storm and tsunami inundation.

The GEBCO_2020 Grid is the latest global bathymetric product released by the GEBCO and has been developed through the Nippon Foundation-GEBCO Seabed 2030 Project. The GEBCO_2020 Grid provides global coverage on a 15 arc-second grid of 43,200 rows × 86,400 columns, giving 3,732,480,000 data points.

But IHO does not limit its activities to governmental bodies, oceanographers, and industry partners. IHO's Crowdsourced Bathymetry Working Group (CSBWG) examined how best to incorporate, manage, and use bathymetric data acquired by other than conventional means and develop principles and guidelines to enable the appropriate collection and use of the maritime version of citizen science called *crowdsourced bathymetry*. In 2019, the CSBWG, comprising representatives from national HOs, academia, and industry finalized the first edition of a guidance document that sets out the key issues regarding crowdsourcing—both from a collector's and a user's perspective. The resulting guideline named IHO B-12 "Crowdsourced Bathymetry Guidance Document" provides general advice and information for those considering collecting or using crowdsourced bathymetry.

Capacity building constitutes another important component of the IHO Work Programme. Its scope encompasses all hydrographic needs as it underpins every other activity associated with the sea, including safety of navigation, protection of the marine environment, national infrastructure development, coastal zone management, marine exploration, marine resource exploitation (minerals, fishing, etc.), maritime boundary delimitation, maritime defense and security, and coastal disaster management. The IHO Capacity Building Strategy stipulates that the focus should be on achieving enduring output that will benefit safe navigation, safety of life at sea, protection of the marine environment and economic development, rather than on creating enabling infrastructure, per se.

Objective 3: Increase the Use of Ocean Knowledge and Understanding, and Develop Capacity to Contribute to Sustainable Development Solutions

The IHO develops and sets standards and issues guidance that ensures that hydrographic information is available and can be delivered to users through appropriate harmonized and interoperable products and services. The current maintenance of existing standards and the development of new ones are driven by the need to continue to satisfy the SOLAS requirements of enhancing safety of navigational, and more recently, supporting the implementation of "e-navigation", which is being led by the UN's IMO. Both elements require easy access to standardized high-quality digital geospatial information that can support marine spatial management. Accordingly, the IHO continued to work on its S-100 framework to support the creation and maintenance of interoperable maritime data product specifications compliant with the ISO-19100 series of geographic information standards. Product specifications for electronic navigation chart (S-101), bathymetric surface (S-102), surface currents (S-111), marine protected areas (S-122), marine radio services (S-123), marine traffic management (S-127), and underkeel clearance management (S-129) for vessels navigating in waters of restricted depths have received approval already. The series also includes a product specification for maritime limits and boundaries (S-121). The purpose of S-121 is to provide UN Division for Ocean Affairs and the Law of the Sea (DOALOS) with a suitable format for the exchange of digital vector data pertaining to the maritime boundaries, limits and zones of states to meet their respective UNCLOS deposit obligations.

Numerous IHO member states currently engage in significant efforts to establish regular and frequent services utilizing such data sets with national and regional coverage. Since the S-100 framework and the associated web-based infrastructure is not limited to host data product specifications native to the hydrographic domain, the IHO is proactively supporting the expansion of the S-100 concept to related domains such as maintenance of fixed and floating aids to navigation under the remit of the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), weather and sea ice coverage under the remit of the World Meteorological Organization (WMO), rout plan exchange format (IEC), inland electronic charting standardized by the Inland ENC Harmonization Group, and oceanography (IOC). A notable progress was made with the WMO weather wave hazards overlay (S-412) designed for Electronic Chart Display and Information Systems (ECDIS) supporting marine surface navigation. IHO's S-100 approach is potentially applicable to all sorts of marine information including chemistry and biology of the oceans resulting in interoperable data sets to form "the digital aquarium" to let ocean science dive in.

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COMMENTARY

MTS and the Ocean Decade

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The Marine Technology Society (MTS) is a member of the Ocean Decade alliance of organizations and represents a key partner for the Intergovernmental Oceanographic Commission of UNESCO (IOC) in realizing *"the science we need for the ocean we want."* If you are new to our organization, MTS is the leading international professional society representing ocean technologists and scientists, while also serving as the vital forum and nexus for the diverse spectrum of maritime industries worldwide. MTS was founded in 1963 to bring together industry, academia, and government to promote awareness, understanding, and the advancement and application of marine technology. A historical review of the Society can be accessed in the 2015 special *Journal* issue "Evolution of the Marine Technology Society: Commemorating the 50th Anniversary of the *MTS Journal*" (November/December 2015, Volume 49, Number 6; https://www.ingentaconnect.com/content/mts/mtsj/2015/00000049/00000006). As a partner of the IOC, over the next 10 years, MTS will use its resources to contribute to the planning process, host and organize events, communicate, and provide in-kind support to promote the Ocean Decade's vision.

Contribute to the Planning Process

Although the Ocean Decade has been launched, the planning has just begun. MTS members are a diverse amalgam representing the global ocean technology community. MTS can serve as a concentrator of the viewpoints of this important sector, providing IOC ideas related not only to technologies, but also to meaningful methodologies for implementation and transition into operational products and services.

As a professional society, MTS is well versed in developing Strategic and Implementation Plans, but you may not realize we are also called upon to play key roles in developing other important intergovernmental plans, guidelines, and policy documents. While our expert staff facilitates these, we derive our expertise from our members—subject-matter experts from every facet of the global ocean technology and industrial community. Our organizational structure is largely formed along disciplines and areas of expertise (more than 25 Professional Committees, such as Unmanned Maritime Systems, Pollution, Marine Education, Ocean Observing Systems, etc.). One area for which MTS is globally recognized in their leadership of developing accepted practices is our Dynamic Positioning (DP) Professional Committee. This group of industry experts are employed by several major international companies, many of whom are competitors in the business world, but who work together under the MTS umbrella to develop "Best Industry Practices" and Guidelines in a large-scale offshore operation where mistakes or missed steps can result in both loss of life and very expensive equipment (like ships). The Plans, Documents, and Guidelines developed by the MTS DP Professional Committee have not only been adopted by the United States Coast Guard (USCG) as "the gold standard," owing to our globally recognized leadership and expertise in this domain, MTS was asked by the USCG to assist in their update of the International Maritime Organization MSC Circular 645, which dictates the international guidelines for ocean-going vessels with DP systems. The MTS DP Professional Committee demonstrates how the Society can serve as an honest broker and subject-matter expert for building critical regulatory policy in an international forum.

Host and Organize Events

MTS, with our IEEE Ocean Engineering Society (OES) partner, hosts two major international OCEANS Conferences each year—one in North America and one alternating between Asia and Europe, convened in major coastal cities in IOC member states around the globe. This represents 20 opportunities over the Ocean Decade for like-minded people to discuss issues important to forwarding the success of the Ocean Decade activities. We also regularly convene smaller "pop up" TechSurges (purpose-focused workshops, convened nimbly and efficiently) that can be tailored to Ocean Decade objectives.

The OCEANS conference now has an impressive portfolio of successful conferences around the globe. When it was apparent that COVID-19 would cause a disruption to our events, we immediately combined our North American (Gulf Coast, Mississippi) and Asia (Singapore) conferences to establish our first virtual and successful "Global" conference. Prior to the COVID-19 disruption, the past five non-North American OCEANS have been held in Marseille, Kobe, Aberdeen, Shanghai, and Genova; and the next five in Porto (virtual), Chennai (see member contributions in this *Journal* issue), Limerick, Halifax, and Singapore. Locations for OCEANS conferences during the second half of the decade are yet to be identified and we would be honored to make those decisions in concert with IOC. The attendance of these conferences ranges from 1,500 to 3,000 attendees and themes and topics are decided individually for each conference by MTS, IEEE OES, and the Local Organizing Committee.

This year's OCEANS conference will again be Global by combining our North American (San Diego) and Europe (Porto) conferences; however, this will be a hybrid having both in-person (San Diego) and virtual components (both locations). This will be an officially registered Ocean Decade event. Dr. Vladimir Ryabinin, IOC Executive Secretary, will give opening remarks to kick-off this Ocean Decade event (see commentary in this issue). MTS and IOC held a brainstorming session and generated the following ideas as potential activities at this and future year's OCEANS conferences:

- Keynote Speaker—an invited IOC Ocean Decade leader to serve as a Plenary Speaker to give an annual update at each year's meeting;
- Town hall—highly inclusive incorporating showcasing of flagship programs and partners;
- Mainstreaming the Ocean Decade into the technical program/sessions—devote a "Technical Track" (comprising several Technical Sessions, with up to six presentations made within each) made by researchers, engineers, policy makers, and educators involved in the Ocean Decade;
- Exhibition—in-person booth for IOC and other members;
- Animated booth (virtual);
- Ocean Decade Alliance meeting;
- Film festival;
- Early career ocean professional (ECOP) activities that include the new MTS ECOP Section and Board Member;
- Black tie dinner/gala;
- Loop of Ocean Decade videos on different supports online and/or in venue; and
- Endorsement of conferences as an Ocean Decade Action.

Additionally, the nimbleness that we have exhibited at our TechSurges and Workshops (described in more detail below) could also be a vehicle for targeted technical sessions that will emerge from IOC developments as discussions during the Ocean Decade evolve.

Communicate

MTS, headquartered in Washington, DC, is a fully staffed operation of professionals specializing in all forms of 21st century communication platforms and methods to keep our worldwide constituency informed and in touch with one another. This includes a peer reviewed Journal, monthly newsletter (*Currents*), content-rich website, online webinars, and all manner of social media. As an example, this special issue of the *MTS Journal* is the first in a multi-volume series devoted to Ocean Decade themes and serves as MTS' first official, registered Ocean Decade activity. This issue serves as an introduction to the Ocean Decade and we plan to publish one special issue in each successive year to track progress and advances in technologies as they relate to the Ocean Decade.

MTS and Ocean Exchange™ have teamed up to offer a joint webinar series, Engaging with the Blue Economy, as a registered U.S. National Committee Decade event (https://www.mtsociety.org/index.php?option=com_jevents&task=icalrepeat.detail&evid=14&Itemid=182&year=2021&month=06&day=02&title=engaging-with-the-blue-economy-offshore-energy&uid=5a596feafd863489ed2413dd7694e7b3). This webinar series began in March 2021 and focuses on all facets of the Blue Economy with the goal of recognizing the importance of the Ocean in our daily lives.

Another collaborative Ocean Decade activity currently in planning between MTS and Global Ocean Observing System (see GOOS commentary in this issue) is a series of topical dialogues around the growing commercial and operations research sectors of the Ocean Observing Enterprise, titled "Ocean Observing for 2030—Dialog with the Industry." MTS is uniquely positioned to bring its industry members into the conversation to better understand the opportunities and barriers for their participation in the Ocean Observing Enterprise that aims to support the Ocean Decade. Potential topical sessions include an assessment of the market and downstream services that are needed, providing data as a service, recognizing new networks and business models, disruption of the supply chain, workforce for a New Blue Economy, state-of-the-art marine technology discussions, and cross pollination of trends and technologies from sectors outside of maritime. Topical sessions will be designed as virtual webinars that result in a collection of white papers or special journal issue publications. We look forward to hearing from our members for ideas and participation.

There are some other important forms of "communications" that transcend into the previous category of "hosting and organizing events." We have had tremendous success with what we have come to call TechSurges. They can be quickly put together in order to respond to some timely event (like the Deepwater Horizon oil spill); they may be a 3-day "workshop" with in-water demonstrations of the latest technologies; or a morning session appended to the beginning of some other organization's meeting that was already planned. The point is, these are a means of bringing the right people together (sometimes quickly) at the right place and time to address a topic of current interest. From these TechSurges can be developed Recommendations, Key Observations, Publications for a special issue of the *MTSJ,* or even the basis of future Policy.

As specific examples, 2 weeks after 2012's "Superstorm Sandy," MTS hosted a TechSurge, convening experts in meteorology, emergency response, severe weather forecasting and instrumentation, which provided a foundation for a budget increase to NOAA's hurricane forecasting improvement. More recently, we hosted a TechSurge focused on mapping the U.S. Great Lakes to contribute to the larger Seabed 2030 effort. These are very effective means of both communication as well as community engagement.

And on the topic of community engagement (another form of communication), our emphasis is on education, nurturing and supporting the next generation(s). We accomplish this in many forms, from scholarships and mentoring programs to maintaining MTS Student Sections at dozens of universities around the world. Beginning in January, a new Board of Directors position, Vice President of ECOPs, was established and filled to ensure MTS was listening to the next generation of ocean technologists, and a new ECOP Section was established. One of the most exciting activities (pre-COVID-19), which draws in not only youths but also local communities, has been the MTS Marine Technology Camps that provide young students what is usually their first opportunity to go offshore on vessels, deploy marine technologies, and to conduct real science. This provides them a very personal and memorable idea of what is going on in the waters around their local towns or villages. This successful program is expandable, adaptable, and transferrable worldwide.

MTS also works in partnership with the Office of Naval Research (ONR) and the Office of Naval Research-Global (ONR-G) and IEEE/OES to host two Student Poster Competitions each year that highlight rising marine talent and include as many students as we can in our meetings. An analog focused on the Ocean Decade is easy to imagine.

Throughout the Ocean Decade, MTS staff will keep our members informed of related activities and news through multiple forms of communications—website, LinkedIn, Twitter, and Instagram.

Provide In-Kind Support to IOC

Because so many of the objectives and desired outcomes of the Ocean Decade are so closely aligned with the MTS mission, strategic coordination between IOC and MTS will in large part allow us to serve both organizations' objectives within our existing (and stable) financial constraints.

Though MTS is in the enviable position of being financially sound, we still would obviously not be able to justify to our membership using their treasury to support the UN (with some exceptions like our modest support to sponsor past receptions during IOC Assemblies). However, the pursuits we presently undertake to support our stated mission could easily be harmonized to also serve the goals and outcomes of the Ocean Decade. This would of course require working closely and continuously with IOC throughout the initiative as a Partner, as we are now.

A good picture of the breadth and depth of expertise found among our ranks can be found by taking a look at the titles of our 25+ Professional Committees (https://www.mtsociety.org/committees). These Committees track remarkably closely to some of the main areas in which IOC operates, from Ocean Observing, Tsunami early warning systems to Marine Policy, Marine Education, and so on. In a very real sense, aside from providing a forum for the "triple helix" of our constituency (Industry, Academia, and Government) to meet and share their developments and discoveries, in a very real sense our mission is quite similar to that of the IOC—capacity building.

In summary, MTS represents a vital key to the success of the stated objectives of the Decade of Ocean Science for Sustainable Development. MTS is excited to utilize our resources working closely with the IOC over the course of the Ocean Decade to achieve *"the science we need for the ocean we want."*

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The Nippon Foundation-GEBCO Seabed 2030 Project: The Most Ambitious Seafloor Mapping Initiative in History

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The most ambitious seafloor mapping initiative ever—The Nippon Foundation-GEBCO Seabed 2030 Project—is gaining more and more traction every month. The mission is to achieve a bathymetric map covering all of the world's oceans by 2030. At the outset of the Project, which was officially launched at the United Nations Ocean Conference in 2017, this was regarded by many as a far-reaching goal and a somewhat daunting prospect. But now, 4 years on, academics, engineers, and surveyors from all over the globe have increasingly started to believe that it really is possible to develop a definitive map of the world's ocean floors that will be freely available for all. So how did this immense undertaking start? How did we get where we are now? And where will this journey end? Read on to find out.

In June 2016, a large group of scientists, policymakers, and representatives from both the public and private sector gathered in the Principality of Monaco for the Forum for Future Ocean Floor Mapping. Initiated by The Nippon Foundation, the Forum outlined what would eventually become Seabed 2030. Of course, it was no coincidence that Monaco was the host of this prestigious event. After all, in 1903, Prince Albert I of Monaco was involved in founding the General Bathymetric Chart of the Oceans (GEBCO), which was later followed by the establishment in 1921 of the International Hydrographic Bureau—the headquarters of what is now the Secretariat of the International Hydrographic Organization (IHO). Ultimately, GEBCO fell under the auspices of the IHO, having been run previously by the team of the Oceanographic Museum of Monaco. In fact, Prince Albert I was the first in a long line of sovereigns of Monaco to be ambassadors for oceanography in general, and seabed mapping in particular, which continues to this day. Subsequently, IHO joined forces with the Intergovernmental Oceanographic Commission (IOC) of UNESCO to jointly manage the GEBCO program with a mandate to map the entire ocean floor. The backbone of GEBCO, and therefore of Seabed 2030, is formed by a community of scientists, technicians, engineers, and surveyors working together across the globe.

It is important to note that The Nippon Foundation has had a longstanding affiliation with the GEBCO community. Recognizing the lack of manpower that was hindering the progress of ocean mapping, The Nippon Foundation—together with GEBCO—established a training program at the University of New Hampshire in 2004 to raise a new generation of scientists and hydrographers in ocean bathymetry. At the closing of the Forum in Monaco, Mr Yohei Sasakawa, Chairman of The Nippon Foundation, announced the resolution to partner again with GEBCO to work together toward achieving a bathymetric map covering 100% of the world's oceans by the year 2030. This transformed what started out as a purely academic project into a worldwide endeavor on an unprecedented scale.

Notable Increase in Data

To examine how this immense undertaking started, we need to go back more than 100 years. While preparations had started before the turn of the 20^{th} century, it was at a meeting in 1903, that Prince Albert 1 generously offered to organize and fund the new "la Carte Générale Bathymétrique des Océans." This GEBCO atlas comprised a series of global charts that showed contours based on the available data at that time—which had been generated by a relatively small number of soundings taken by lead-line-type sounding devices. This chart series was updated regularly throughout the 20^{th} century by a fervent group of academics. Their work was largely a long-distance partnership, interspersed with occasional conferences and meetings.

Although GEBCO has been one of the longest running hydrographic and oceanographic programs, it remained under the radar for many decades, with only those working at the very heart of chart production aware of its existence. That is until the start of the Seabed 2030 Project in 2017, some 114 years after that defining moment of 1903. More recently, the GEBCO map that was available in 2017 showed that only 6% of the ocean floor had been mapped adequately. Only a few years later in 2020, GEBCO published an updated map showing an increase to 19% mapped. That impressive upsurge in data was largely due to the Seabed 2030 Project getting off to such a flying start in its first 3 years. Casting the net so widely attracted partners from many different areas of society, including academia, government, the private sector, the nonprofit sector, and many more who were willing and able to contribute existing sparse soundings and even much fuller datasets to help expand the GEBCO database.

Worldwide Organization

The organization has rapidly matured over the past 4 years, and Seabed 2030 comprises four Regional Centers and a Global Center. One hosted by the Alfred Wegener Institute in Bremerhaven, Germany, is responsible for the Southern Ocean; a second hosted at Columbia University, New York, USA, takes care of mapping activities in the Atlantic and Indian Ocean; a third, jointly hosted at Stockholm University, Sweden and the Center for Coastal and Ocean Mapping, University of New Hampshire, assembles data for the Arctic and North Pacific; and the fourth center is hosted at the National Institute for Water and Atmospheric Research in New Zealand and to oversee the South and West Pacific. The British Oceanographic Data Centre at the National Oceanography Centre in Southampton, UK, serves as the Global Center, bringing together regional contributions and publishing the freely available digital GEBCO map. Last but not least, in strong support of Seabed 2030, the IHO Data Centre for Digital Bathymetry, hosted in Boulder, Colorado, by the U.S. National Oceanic and Atmospheric Administration, engages with data donors and other national repositories to archive the source datasets that are so crucial to the mapping mission. The Seabed 2030 team, led by the Project Director working in collaboration with The Nippon Foundation and the GEBCO Guiding Committee, and with some 26 experts across the various centers and supported by the wider GEBCO community, is a truly global entity.

Growing Need for Seafloor Knowledge

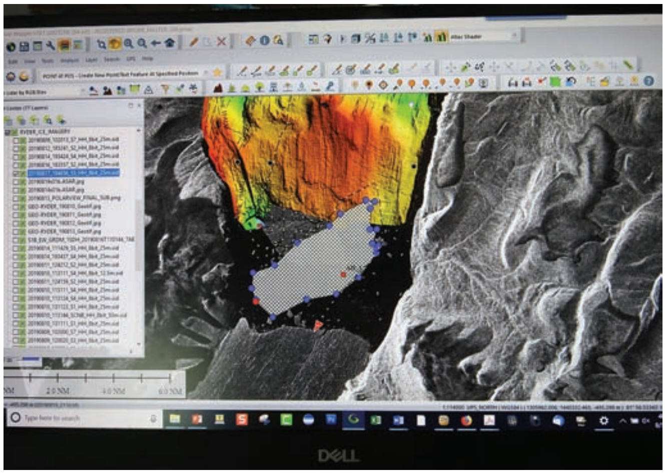
There is an increasingly urgent need for a bathymetric map fully covering the world's oceans. In the past, often the first thoughts that come to mind in the need for mapping are for safe navigation or perhaps to support localized scientific research. But it is never that simple and with the oceans covering more than 70% of the Earth's surface, how oceans are managed and how ocean health is improved are key to the survivability of planet Earth; yet with only just under 20% of the oceans mapped to date, there is so much more to discover. Globalization has led to exponential growth in ocean business and the use of the oceans. There is an enduring imperative to ensure that marine resources are used sustainably; that coastal communities are protected; and that critical infrastructure is established and maintained responsibly. Necessary marine transportation must be facilitated safely as most work to explore ocean-based initiatives for energy transition from fossil fuels to renewable sources. To make informed decisions and as a basis upon which to coordinate the wide and complex range of ocean activities, an adequate knowledge of the seabed shape is required. Underwater topography is fundamental to the circulation of ocean currents and associated effects on climate change, weather systems, tides, and tsunami wave propagation. It is also key base layer in understanding and protecting the habitats of marine species, supporting the monitoring and mitigation of marine pollution and protection of the very resources upon which the world is so reliant. It is clear that the race to map the remaining 80% of the world ocean floor is on.

Technological Boost

Technological advancements have accelerated the mapping process by making data acquisition increasingly more efficient and more affordable. The introduction of modern multibeam sonar systems delivered a step change in the volume and quality of bathymetry gathered. The concept of uncrewed and autonomous vessels has rapidly become a reality with their ability to remain out at sea for prolonged periods of time, thus improving the capability to efficiently survey previously uncharted frontiers of the ocean. Closer inshore, and subject to the right water conditions, satellite-derived bathymetry of shallow waters will also boost the ability to gather

FIGURE 1

Seabed data—A snapshot of the data captured by the multibeam sonar on Oden. The red arrow shows where Oden is, with the hashed area yet to be scanned. Captured by Professor Larry Mayer on the expedition to the 2019 Ryder Glacier, Greenland.



data in more challenging and/or remote coastal areas. And once the data has been acquired, the rise in automated solutions enables it to be processed faster than ever before—often in real time. Another innovation that has the potential to make a huge contribution to Seabed 2030 is Crowd-Sourced Bathymetry. There are countless vessels—from pleasure craft and fishing vessels through to cruise liners and container ships—that are fitted with positioning systems and echo sounders for safety of navigation purposes. Through installation, and operation, of inexpensive data loggers, position and depth data can be captured and so the "power of the crowd" can be embraced in a way that will contribute invaluable new datasets to the GEBCO map on a regular basis. Figures 1-3 show a research expedition to the remote Ryder Glacier, including previously unchartered waters.

The Shell Ocean Discovery XPRIZE was instrumental in new technology being incorporated into ocean mapping and, of course, Seabed 2030 has benefitted from this. The GEBCO-Nippon Foundation Alumni team won the first prize in this global competition aimed at stimulating new deep-sea technology for autonomous, fast, and high-resolution ocean exploration. The team's prize-winning solution, SEA-KIT, integrated existing technologies and ocean-mapping experience with a robust and low-cost unmanned surface vessel equipped with a novel, cloud-based data processing system to facilitate rapid seabed visualization. Winning the Shell Ocean Discovery XPRIZE gave the team an enormous

FIGURE 2

Oden on the expedition to the Ryder Glacier. Oden is the icebreaker that was the base for the expedition. It was home to the laboratories, crew, and equipment for the duration of the journey. Taken by Professor Martin Jakobsson, 2019.

FIGURE 3

Seabed sampling—one of the cores procured by the gravity corer onboard the icebreaker Oden that penetrates into stiff sediments in the sea bed. From left to right, Matt O'Regan (Stockholm University), Markus Karasti (Stockholm University), and Tom Cronin (USGS). Taken by Professor Martin Jakobsson on the 2019 expedition to the Ryder Glacier.

boost and helped focus state-of-the-art technology in the drive to accelerate ocean mapping efforts, something that is at the very heart of Seabed 2030. The team also decided to contribute the prize money of $4 million to work toward the achievement of a complete map of the ocean.

Collaborative Partnerships

The Seabed 2030 Project continues to gather pace, helped by the formation of numerous partnerships across all sectors of society. Of course, some are with private-sector companies, including Fugro and PGS, both of which donated significant data some of which had been acquired in the search for MH370—the aircraft that went missing in the Indian Ocean in 2014. Other organizations that have made resources available for the Project include the Schmidt Ocean Institute, Caladan Oceanic, the Global Multi-Resolution Topography Data Synthesis, and the Scripps Institution of Oceanography; the latter two having very recently signed cooperation arrangements with Seabed 2030 aimed at increasing our understanding of the oceans. To date, Seabed 2030 has over 155 partnerships and it is safe to say that many more organizations are likely to join the Project in achieving its aim.

The Next Ten Years

The need for more data is increasing with a growing sense of urgency, and technological advancements should enable that need to be met. The policymaking environment is also favorable; the United Nations Sustainable Development Goals (SDGs) that were set in 2015 are providing a valuable springboard for initiatives like Seabed 2030. The Project's mapping efforts directly support SDG 14: to conserve and sustainably use the oceans, seas, and marine resources. Besides that, the United Nations has declared the current decade to be the "Decade for Ocean Science." Running until the end of 2030, this coincides with the most ambitious phase of Seabed 2030, during which approximately 80% of the seafloor still needs to be mapped. The leadership of The Nippon Foundation, the IHO and the IOC, the increasing importance of the ocean for the global Blue Economy, the growing sense of urgency surrounding measures to tackle climate change, and the advancement of technology … all these factors are helping Seabed 2030 to gather further momentum in its mission to map the world ocean floor. This ambitious initiative—the origins of which arguably began almost 120 years ago—looks set to become the most successful seafloor mapping project in the history of humankind.

COMMENTARY

How Innovations in Mapping Will Help Support the Ocean Decade

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ABSTRACT

A wholly mapped ocean is one of the foundational goals of the United Nations Decade of Ocean Science for Sustainable Development. This multifaceted initiative aims to reverse the cycle of decline in ocean health and facilitate improved conditions for sustainable ocean development worldwide. Meeting this goal will require significant innovations in marine geodesy and survey. The following commentary details how innovations in satellite positioning, satellite imaging technology, remote operations, autonomous vehicles and robotics, and analytics and cloud automation are helping to provide safer, more efficient, cost-effective and sustainable marine survey and mapping solutions in support of the Ocean Decade. Real-world innovation examples from Geo-data specialist company Fugro are provided.

"The calculus of innovation is really quite simple: Knowledge drives innovation, innovation drives productivity, productivity drives economic growth." This quote by American scientist William Brody succinctly captures the importance of innovation to the recently launched United Nations Decade of Ocean Science for Sustainable Development. A multifaced initiative to develop a common, global framework for ocean science, the Ocean Decade aims to reverse the cycle of decline in ocean health and facilitate improved conditions for sustainable ocean development across the globe. Innovation will play a key role in the Ocean Decade, helping to deliver the massive knowledge gains needed to achieve "the science we need for the ocean we want".

While the Ocean Decade is broad, covering many aspects of ocean science, one of its foundational goals is a wholly mapped ocean. As such, innovation in marine geodesy and survey are considered critical and will include both technologies (systems) and techniques (solutions). As a leading Geo-data specialist, with research, development, and innovation at the core of our strategy, Fugro is helping to support the Ocean Decade with marine geodesy and survey technologies and techniques.

A Framework for Innovation

In developing the Implementation Plan for the Ocean Decade, the Intergovernmental Oceanographic Commission of UNESCO (IOC) created the Decade Action Framework, as presented in Figure 1, to guide the design and implementation of initiatives that will support the Ocean Decade (IOC, 2020). The highest level of this framework is a set of ten Ocean Decade Challenges, which represent the initiative's most immediate and pressing priorities. The need for ocean mapping is detailed in Ocean Decade Challenge 8, which states:

> *Through multi-stakeholder collaboration, develop a comprehensive digital representation of the ocean, including a dynamic ocean map, which provides free and open access for exploring, discovering, and visualizing past, current and future ocean conditions in a manner relevant to diverse stakeholders.*

The second level of the Decade Action Framework comprises three Ocean Decade Objectives, which guide the multi-step, iterative and cyclical process required to fulfill the Ocean Decade Challenges and ultimately contribute to fulfillment of the Ocean Decade Outcomes, or "the ocean we want". The three Ocean Decade Objectives include:

1. The identification of ocean knowledge that is required for sustainable development.
2. The generation of the data, information, and knowledge for the development of a comprehensive understanding of the ocean, its components, and its interactions.
3. The use of the generated knowledge and understanding of the ocean to deploy solutions for sustainable development.

FIGURE 1

The Decade Action Framework (© Intergovernmental Oceanographic Commission – UNESCO).

The application of these three objectives to Ocean Decade Challenge 8 connects knowledge, innovation, productivity, and sustainable development, while also articulating the importance of innovation in marine geodesy and survey.

Marine Geodesy Innovation to Support the Decade

Approximately 30 years ago, the availability of Global Positioning System (GPS) technology helped revolutionize the field of marine geodesy and survey. By providing a global and continuously available positioning system on a single geodetic reference frame, GPS transformed the way marine navigation, positioning and survey are performed. Instead of local or regional shore-based radio positioning systems operating on separate datums, global satellite-based positioning systems provided a single global datum 24 h a day. This transformation started with survey and mapping applications but has since broadened to cover virtually any marine application and almost every marine platform in the world. From the largest cruise ships to stand-up paddle boards (via the smart watch on the wrist of the paddle boarder), platforms are now positioned in real-time by GPS and/or other Global Navigation Satellite Systems (GNSS) that have since been introduced.

While this technology revolution originally occurred in the early 1990s, a series of subsequent innovations have increased the availability, accuracy, and reliability of GNSS, while decreasing its costs. These improvements were made available through the addition of other satellite navigation systems, augmentation systems and techniques, and miniaturization. As a result, International Maritime Organization Safety of Life at Sea (SOLAS) requires that virtually every ocean-going vessel be equipped with GNSS systems to support marine navigation and positioning (NAVSREGS, 2017). This requirement, combined with SOLAS mandates for echosounders and communications systems for measuring water depth and reporting position and emergencies, makes it possible for all ocean-going vessels to help build a digital representation of the ocean, through a strategy called crowdsourced bathymetry. The International Hydrographic Organization defines crowdsourced bathymetry as depth measurements from vessels, collected using standard navigation instruments, while engaged in routine maritime operations; this approach has the power to significantly improve the global coverage of ocean bathymetry.

Additional GNSS technologies and techniques continue to be introduced that will support marine navigation, positioning, and survey in support of the Ocean Decade. For example, in addition to GPS, there are now three other global GNSS systems

(GLONASS, Beidou, and Galileo) in various stages of maturity. By combining positioning from multiple constellations, Fugro has developed a set of GNSS augmentation services, which significantly improve the accuracy, availability, and reliability of standalone GNSS solutions. Most significant and relevant to the Ocean Decade may be the high-performance positioning solutions now available in high latitudes (the Arctic and Antarctic), where traditional GPS-only solutions struggle.

Furthermore, as outlined above, GNSS has become an essential element of the worldwide information infrastructure. Marine navigation and survey are increasingly dependent on quality satellite positioning services, the integrity of which can be compromised through exposure to cyberattacks. Security is not a built-in feature of GNSS open services, and low-received power as well as unencrypted civil signals are vulnerable to jamming and spoofing attacks. To mitigate these risks, Fugro has introduced a service that offers GNSS navigation message authentication to cross-check the satellite navigation message in our global reference network, providing a digital signature to the user's GNSS receiver and clearly indicating any potential threat. This capability is extremely important on autonomous vehicles, which are becoming increasingly relevant to marine survey and mapping applications.

Marine Survey Innovation to Support the Decade

While marine geodesy experienced its innovation revolution approximately 30 years ago, the marine survey innovation revolution is happening now. Survey and mapping systems and solutions are now advancing at an unprecedented pace, driven primarily by innovations in core technologies, such as remote operations, autonomous vehicles and robotics, and analytics and cloud automation. The pace, breadth, and sophistication of these innovations is now very high and will ultimately provide safer and more efficient, cost-effective, and sustainable marine surveying and mapping solutions in support of the Ocean Decade.

Another exciting area of innovation is related to satellite imaging. The growing availability and reduced cost of satellite remote-sensing data, combined with improved algorithms and analytics, mean that satellite solutions are becoming an increasingly important tool for marine survey in shallow coastal waters with reasonable water clarity. While satellite-derived bathymetry (SDB) solutions have been available for approximately 25 years, the technology has matured appreciably over the past decade, and improvements will only increase further with the advent of cube satellites, which significantly increase persistence and reduce costs of satellite imagery.

Capitalizing on these advancements, Fugro has developed a satellite-based solution for coastal monitoring. While it does not provide absolute depths, it does provide a very efficient and cost-effective approach to detecting the location and scale of coastal change. This information can then be used to determine if additional survey is required using more precise techniques (via SDB, lidar, or multibeam) at very discrete and specific locations, thereby eliminating the need to resurvey large areas of seabed where change is not occurring.

Despite using remote technologies in offshore operations for some time, the relevance and value of these innovations were highlighted to Fugro anew during the recent Covid-19 outbreak and associated lockdowns. Advances in communications, telemetry, and data compression have all contributed to the development of remote command and control technology that allows qualified staff to increasingly conduct their work from shore-based office environments instead of onboard vessels.

Fugro first introduced remote operations in 2013 and, since then, the scope and scale of these remote services has grown significantly. From eight remote operations centers located around the globe, Fugro personnel are performing a wide range of offshore activities onshore, including positioning and navigation services, the collection of multibeam and other marine sensor data, the processing and dissemination of acquired data, and even the piloting of remotely operated vehicles (ROVs). With more staff now executing these offshore projects from onshore, Fugro can acquire and deliver data faster, with improved operational safety, increased business continuity, and a significantly reduced carbon footprint.

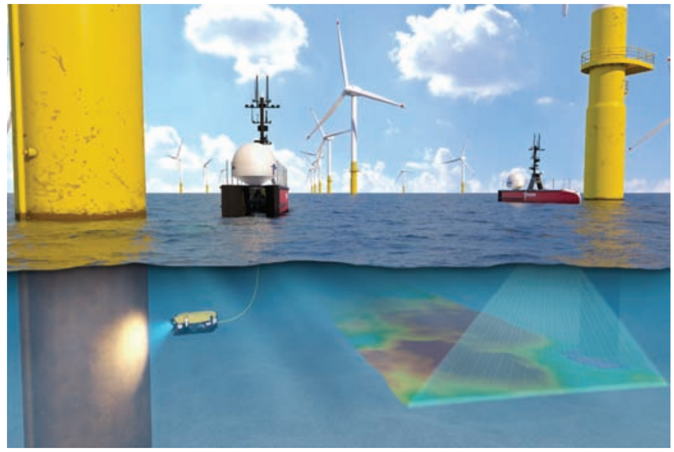
Advancements in remote operations have also contributed to innovations in autonomous and uncrewed platforms. Innovations are occurring in the water with autonomous underwater vehicles (AUVs), on the water with uncrewed surface vehicles (USVs), and in the air with uncrewed aerial vehicles (UAVs). While each platform supports different aspects of marine survey and mapping, they all share similar technology goals and challenges, including sensor miniaturization,

FIGURE 2

Fugro's Blue Essence USV (© Fugro).

FIGURE 4

Illustration of Fugro's remote and autonomous solutions performing ocean mapping and ocean observations at an offshore windfarm development (© Fugro).



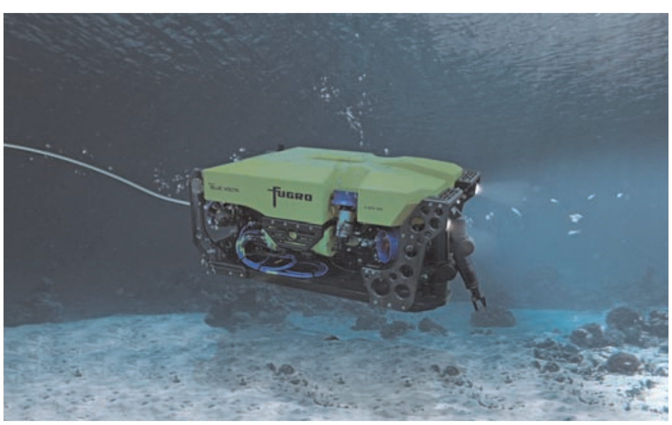
sustained power, operational endurance, and collision avoidance. Of the three technology platforms, AUVs are the most mature, having operated without human intervention for years. These systems tend to be used in deeper water near the seafloor, meaning they do not have the same traffic management, collision avoidance and regulatory requirements as UAVs and USVs. Ultimately, the goal for USVs and UAVs is to reach the same level of autonomy as AUVs but, until the collision avoidance technology matures and a regulatory regime is established, uncrewed operations will still require some level of supervision.

Fugro has been offering AUV-based high-resolution survey and mapping solutions for nearly two decades. Even though this technology tends to be relatively mature compared to its USV and UAV counterparts, it continues to benefit from significant advancements in terms of power, endurance, and sensor payload. With respect to aerial mapping and remote sensing, Fugro now offers a bathymetric lidar capability for shallow water coastal mapping that can be offered from UAVs. Known as RAMMS (Rapid Airborne Multibeam Mapping System), the technology has to date been operating from fixed-wing UAVs and will soon also be operated from rotary wing UAVs. More recently, Fugro's Blue Shadow class of USVs has been designed for coastal hydrography and is currently used as a cost-effective force multiplier to increase productivity. Through a partnership with SEA-KIT, Fugro has most recently developed a larger oceangoing class of USVs known as Blue Essence, capable of deepwater mapping, while hosting an eROV or AUV for remote and uncrewed high-resolution mapping, exploration, and characterization applications. Fugro's Blue Essence USV is shown in Figure 2, while Fugro's Blue Volta eROV is presented in Figure 3.

Marine survey data acquisition and processing have also improved as a result of advances in artificial intelligence (AI) and cloud processing.

FIGURE 3

Fugro's Blue Volta eROV (© Fugro).



AI, for instance, has proven essential to the safe operation of autonomous and uncrewed survey platforms, providing route optimization, dynamic line planning, and collision avoidance. It also enables data to be pulled from crewed or uncrewed acquisition platforms, so that it can be accessed in near real time by shore-based clients, processors, analysts, and consultants. Finally, AI and cloud processing are now being used in cleaning, processing and running analytics on integrated survey, and mapping datasets that are increasingly being combined in a digital twin framework.

Conclusions

Within the Decade Action Framework, Decade Actions will fulfill Decade Objectives and achieve Decade Challenges. Decade Challenges will in turn contribute to one or more Decade Outcomes, which ultimately will support the United Nations 2030 Agenda for Sustainable Development and related regional and global policy frameworks (IOC, 2020). Innovation is a common theme throughout the framework, being directly referenced in multiple Ocean Decade Challenges and one Ocean Decade Outcome, while being implied by extension via knowledge references in the Decade Action and Decade Objectives. Given this, the fact that one of the Ocean Decade Challenges involves the development of a comprehensive digital representation of the ocean, including a dynamic ocean map, there is no doubt that the exciting innovation that is currently occurring in marine geodesy and survey, including within Fugro, as depicted in Figure 4, will be accelerated by and contribute to the Ocean Decade.

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PAPER

Technological Trends and Significance of the Essential Ocean Variables by the Indian Moored Observatories: Relevance to UN Decade of Ocean Sciences

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ABSTRACT

The ocean plays a key role in regulating the climate as well as supporting diverse ecosystems. Technology is the key for the sustained and precise in-situ spatio-temporal measurements of the physical, biological, biogeochemical, and near-atmospheric meteorological parameters essential for carrying out effective assessments of the status, variability, and change in the ocean ecosystems and for creating policies at the right time. The United Nations Decade of Ocean Science for Sustainable Development 2021–2030 provides a timeframe to build a comprehensive, sustainable, and data-based informed decision-making global ocean observing system. This demands global-scale investigations, trans-disciplinary science, and mechanisms to integrate and distribute data that otherwise would appear to be disparate. The essential ocean variables (EOVs) conceptualized by the Global Ocean Observing System (GOOS) of UNESCO's Intergovernmental Oceanographic Commission guide observation of the ocean. In order to achieve the goal of UN Decade envisaged and to have an Earth System approach under the World Meteorological Organization reforms, it is imperative to address globally and nationally relevant indicators and assessments, which require increased sharing of data and analytical methods, sustained long-term and large-scale observations, and resources dedicated to these tasks. Technology for observing the ocean is important, which is not addressed in detail in the recent past. In this paper we provide a comprehensive overview of Sensor versus Essential Ocean Variable from our experience in sustained 25 years of moored ocean observation network and collaborating with institutions and experts in the United States and GOOS. An attempt has been made to furnish an overview for any group or nation to start or sustain an observation network using EOVs with guiding principles of Findable, Accessible, Interoperable, Reusable data that is targeted to deliver essential information needed for sustainable development and protecting ocean health.

Keywords: drift, moored buoys, Indian seas, biogeochemical sensor, essential ocean variables

Introduction

The ocean makes up 71% of the planet and provides many services to human communities from mitigating weather extremes to generating the oxygen we breathe, from producing the food we eat to storing the excess carbon dioxide we generate. Thus, a healthy ocean helps to mitigate climate change and its impacts, protect coral reefs and mangroves that offer coastal protection, and protect immense genetic resources. Monitoring ocean stresses is essential due to the increase in the rate of loss of biodiversity, habitat degradation, acidity of the ocean, and accumulation of plastics and other wastes. At the same time, it is essential to monitor the ocean for cyclones/hurricanes, activity across tectonic plate boundaries (fault zones) for providing tsunami early warnings, and the polar ocean for their influence on the rise in the sea-level and climate change perspectives. Considering the strategic importance of the ocean, the UN has proclaimed 2021–2030 as the "Decade of Ocean Science for Sustainable Development" to support the efforts undertaken to reverse the cycle of decline in ocean health and to gather ocean stakeholders worldwide. The goals are aimed in generating scientific knowledge, infrastructure, and partnerships; and to provide data for enacting policies for a well-functioning ocean in support of all Sustainable Development Goals of the 2030 Agenda (Ryabinin et al., 2019).

In-situ ocean observations are imperative for improving the understanding of the ocean-atmosphere dynamics, which are essential for operational oceanography, weather prediction, and climate modelling. The present global ocean observational networks, comprising precision in-situ meteorological and oceanographic sensors, are configured for real-time and delayed-mode coastal and offshore observations using 300 offshore and coastal-located moored surface buoys (MSB), 1,500 drifting buoys, 3,800 ARGO floats, water current profiler moorings, deep-ocean wave buoys, coastal wave rider buoys, tsunami buoys for deep-sea water level measurements, and ice buoys. These precision sensor networks enable data collection on near-surface stratification, heat storage and sea surface temperature (SST) enabling studies on large-scale ocean-atmospheric interactions, mixed layer dynamics, upper ocean variability, and associated upwelling and down-welling mechanisms during multiple tropical cyclones. The data are essential for weather and climate predictions, such as the El Niño, La Niña, and the Indian Ocean dipole events, which are found to influence global weather and climate patterns (Venkatesan et al., 2018b, 2018c).

Over the past few decades, various global programs such as the Tropical Ocean Global Atmosphere program (TOGA), the World Ocean Circulation Experiments, and the Indian Ocean Air-Sea Interaction Research Initiative-Ocean Mixing Monsoon program were undertaken to understand the status, variability, and change in the ocean ecosystems (Hermes et al., 2019). The TOGA program, carried out from 1985–1994 (McPhaden et al., 2010) motivated efforts to establish a tropical Pacific observing system for studies of El Niño and the Southern Oscillation (ENSO). TOGA led to establishment of the Tropical Atmosphere Ocean Array of moored buoys, which measured and transmitted to shore real-time oceanic and atmospheric parameters to better understand and predict ENSO (McPhaden et al., 1998). Subsequent to TOGA, this moored buoy observing system was expanded into the Atlantic as the Prediction and Research Moored Array in the Tropical Atlantic (Servain et al., 1998; Bourles et al., 2019) and into the Indian Ocean as the Research Moored Array for African-Asian-Australian Monsoon Analysis (RAMA; McPhaden et al., 2009). In addition, beginning in 2010, India established the NIOT-Ocean Moored Buoy Network in the Indian Ocean (OMNI) (Weller et al., 2019) to advance studies of the ocean's role in monsoons. The OMNI buoys measure the essential ocean variables (EOVs) and transmit the data to shore station via satellite. These data sets are being disseminated in GTS file format to the global community through the Indian National Centre for Ocean Information Service (INCOIS Hyderabad). The data is also made available for the research community upon request.

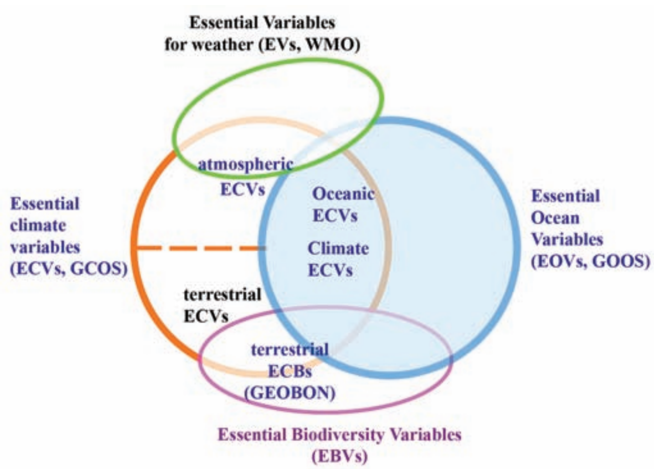
Moored buoys are also operated by various countries in the Arctic region, including India's IndArc for understanding the influence of the Cryosphere (Venkatesan et al., 2018a). Various mobile platforms such as autonomous underwater vehicles, gliders, remotely operated vehicles, and hadal landers enable comprehensive data collection in specific locations. In addition, there are a number of cabled ocean floor observatories that enable the study of the physical, biological, and chemical processes associated with seismic, tsunami, volcanic, ecology, coastal, and atmospheric processes and gas hydrates (Venkatesan et al., 2019).

Concept and Evolution of the EOVs

The concept of the essential climate variables was developed by the UNFCC/IPCC during the late 1990s to focus resources on the collection of minimal data sets necessary to understand the climate variability needed for climate change negotiations (Noufal et al., 2017). The Global Ocean Observing System (GOOS) is engaged in the process of refining, prioritizing, and expanding the EOV. Considering the biogeochemical processes and their potential role on global warming, GOOS have extended the suite of EOV to include the biogeochemical and biological variables (EBV) (Figure 1). The EOVs proposed by the Deep Ocean Observing Strategy consider physical parameters such as ocean bottom pressure, seafloor fluxes, ocean turbulence, and biogeochemical parameters including seafloor respiration, seafloor organic matter, seafloor fluid, gas effluxes, and micro-plastic litter. These efforts are closely coordinated with the Joint Technical Commission for Oceanography and Marine Meteorology, now OceanOPS, which provides a mechanism for the international coordination on the best practices for

FIGURE 1

Ocean status monitoring priorities.



observing, data management, services, and capacity development (Venkatesan et al., 2017b).

Monitoring the influence of the ocean on weather patterns and global climate requires sustained and precise measurement of the ocean physical parameters including the sea-surface and subsurface temperatures, water salinity, dissolved oxygen (DO), and near-ocean meteorological parameters such as surface wind speed and direction, barometric pressure, air temperature, air pressure, relative humidity, solar radiation, wave and precipitation, which are used for analysing heat flux, ocean circulation, monsoon, ocean state, and climate change and provide reliable oceanographic services (Kalyani et al., 2017).

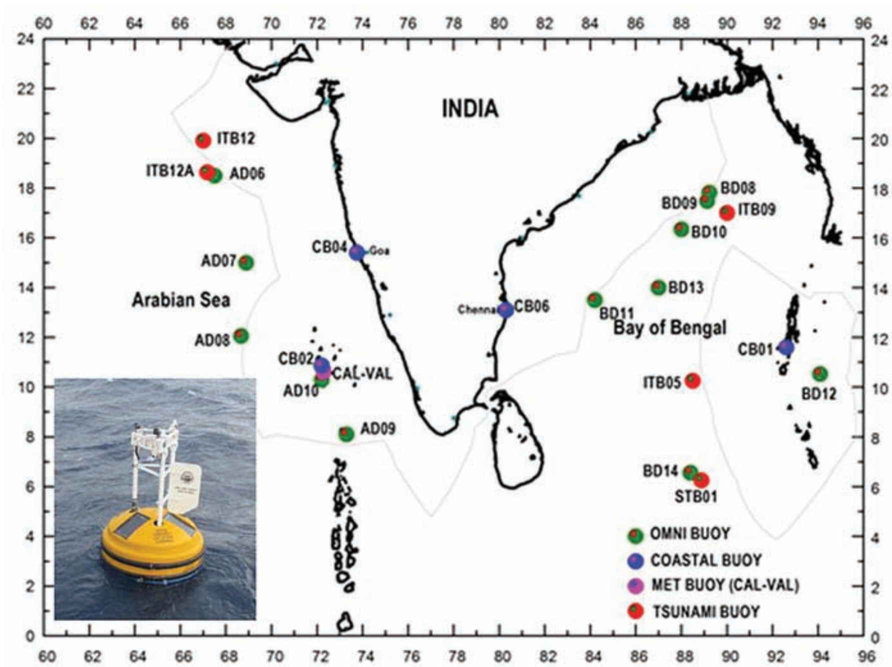
The measurement of dissolved carbon, inorganic carbon, nutrients, nitrous oxide, ocean color, sound, particulate matter, carbon isotopes and transient tracers for characterizing the physical and chemical environment, primary production, ecosystem structure, habitat, spatial distribution and diversity of biomass, energy transfer and the influence of the anthropogenic pressures is essential for studying biological ecosystems. Measurements are required for biogeochemical modelling to understand climate change, and the availability and distribution of food webs (Kumar et al., 2018).

The influence of the cryosphere on the biogeochemical cycles, biological productivity and increase in sea-level rise of the global ocean require analyzing ice-shelf dynamics, paleoclimate, long-term mass balance, energy balance, and hydrological balance. These studies require the measurement of salinity, temperature, DO, photosynthetically active radiation (PAR), fluorescence, turbidity, nitrate, water currents, and ambient noise (Prakash et al., 2018).

While the demands in the spatiotemporal measurements related to the climate, biological, biogeochemical domains are increasing, the Framework for Ocean Observing (FOO) through the sponsorship of the International Oceanographic Commission (IOC) is developing guidelines for a multidisciplinary and integrated ocean observing system for operational utilities, including sustained scientific research in a fit-for-purpose process with user-driven feedbacks (Venkatesan et al., 2017a). The FOO proposes coordination and integration for the routine and sustained observations of physical, biogeochemical,

FIGURE 2

Moored data buoy network in northern Indian Ocean.



and biological EOVs selected by evaluating the readiness, feasibility, and their impact to address societal needs. Increasingly, the continued monitoring of the ocean using EOVs is the basis for assessing ocean health.

Indian Ocean and Arctic-EOV

The Indian Ocean has its unique geography as it is land-locked by the Asian landmass and cannot transport the heat gained to northern latitudes. Moreover, the Indian Ocean gains additional heat from the tropical Pacific via the Indonesian throughflow in its eastern boundary. This unique geography has important implications on monsoon variability, biogeochemical cycles, operational oceanography, and global climate. NIOT has undertaken sustained long-term ocean observations using moored observatories in the northern Indian Ocean at water depths up to 3,000 m to study the variability spanning from intraseasonal to interannual, decadal, and much longer time-scale over the past two decades (Figure 2).

As described in Figure 3, the subsurface instruments that are positioned at 1.2, 5, 10, 20 30, 50, 75, 100, 200, and 500 m water depths are interfaced with the buoy data acquisition system using inductive data links through the mooring. The buoy is programmed to log the meteorological and oceanographic parameters shown in Figure 3 at the predetermined frequency and transmit the data to the Mission Control Center (MCC) at NIOT every 3 h.

The IndARC moored observatory was deployed at 78°57′N/12°01′E, ~1,100 km away from the North Pole (Figure 4), in the Konsfjorden Arctic at a water depth of 192 m to understand the changes in the cryosphere. The Kongsfjorden is chosen for the mooring as the location receives variable Arctic/Atlantic climatic signals between years with measurable effects on the physical and biological systems, and hence it is a natural laboratory for climate change studies. The mooring has an array of ten state-of-the-art oceanographic sensors positioned at discrete depths in the water column (Figure 4). The evolution of the EOVs in Indian and Arctic Ocean are detailed in Table 1. The data sets collected over the past two decades are detailed in Table 2

FIGURE 3

OMNI mooring configuration.

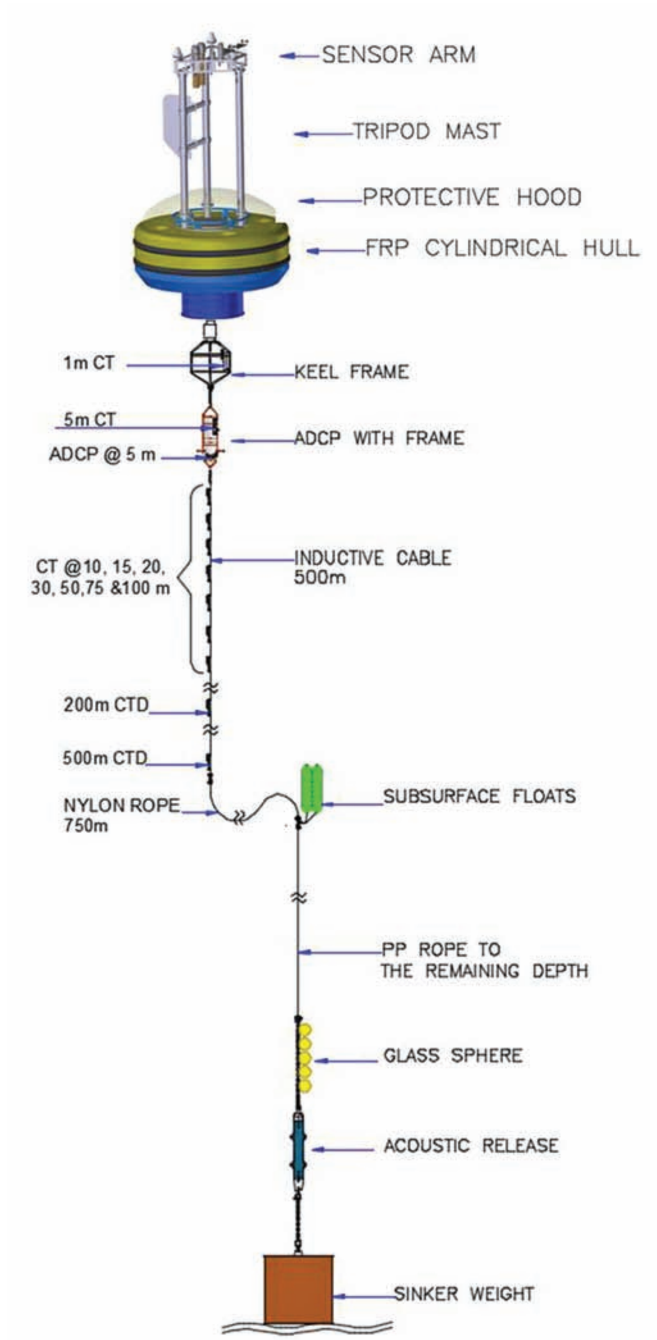


FIGURE 4

India's IndARC mooring in the Arctic.

with the discussion of the sensors used to collect them in the following section.

Barometric Pressure Sensor

Barometric pressure sensors used in the MSB are vital for determining the cyclone genesis, position, and strength of the high and low pressure areas, and their spatio-temporal migration using forecast models. The evolution of the atmospheric pressure measurement technologies dates back to 1643 with the invention of the Torricelli barometer for absolute pressure measurement and the bourdon gauge for relative pressure measurement in 1849. Subsequent technologies include measurements based on potentiometric, resonant, piezoelectric, piezo-resistive, and the recent electrostatic variable capacitance (EVC) types.

Based on the recommendations of the World Meteorological Organization (WMO), pressure sensors with accuracy levels of ±0.3 hPa are mounted in the mast of the MSB at 3 m from the sea level. The semi-diurnal variation in the atmospheric pressure is used for cyclone detection. Under normal conditions, the pressure difference between the present and previous days at the same time shall be < 2.3 hpa, where a threshold of 4 hpa indicates a cyclone (Wijesekera et al., 2016). The atmospheric pressure recorded by moored buoys during the passage of the very severe tropical cyclones in the Bay of Bengalis shown in Figure 5.

In the EVC-type pressure sensor, the pressure sensing element comprises a silicon diaphragm and a substrate. When the pressure varies, the silicon diaphragm bends and changes the capacitance of the sensor, which is converted into pressure reading.

TABLE 1

Evolution of sensors since 1997.

Year	Essential Ocean Variable	Essential Climate Variable + Essential Biological Variable
1997	Air pressure, Air temperature, Humidity, Wave	Surface CT, surface water velocity, DO, pH, Chlorophyll a
2000		
2005		Addition sensors included; temperature profile from surface to 100 m using thermistor
2010 +	Addition sensors included are solar radiation, precipitation	Addition sensors included are conductivity, temperature profile up to 500 m, nitrate, PAR, turbidity

TABLE 2

Data sets collected in Northern Indian Ocean (NIO) and arctic since 2007.

Domain	EOV	Number of Data Sets (Millions)
Marine Meteorology (6.6 million)	Air pressure	0.904
	Air temperature	0.854
	Humidity	0.793
	Wind	2.438
	Net radiance	0.570
	Irradiance	0.495
	Precipitation	0.501
Ocean (37.5 million)	Wave	2.637
	Current	17.661
	Temperature	8.187
	Conductivity	7.979
	Pressure	1.060
Polar (Arctic) (8 million since 2014)	Conductivity	0.29
	Temperature	0.29
	Salinity	0.29
	Pressure	0.29
	Dissolved oxygen	0.06
	Turbidity	0.04
	PAR	0.07
	Nitrate	0.66
	Current	6.06
Total		~54 million

Silicon offers good elasticity, low hysteresis, excellent repeatability, minimal temperature dependence, and superior long-term stability. To ensure reliable measurement in the MSB under harsh offshore conditions, the sensors have built-in overpressure blocking, temperature compensation mechanisms, orientation of the pressure port maintained perpendicular to the direction of wind flow, and a water trap to protect the sensing element from precipitation. The capabilities of the EVC-type barometric pressure sensor are shown in Table 3. Based on the 16 EVC pressure sensor field failures during 0.89 million offshore operating hours, the mean time to fail (MTTF) is 6.35years (Venkatesan et al., 2016a).

Air Temperature and Humidity

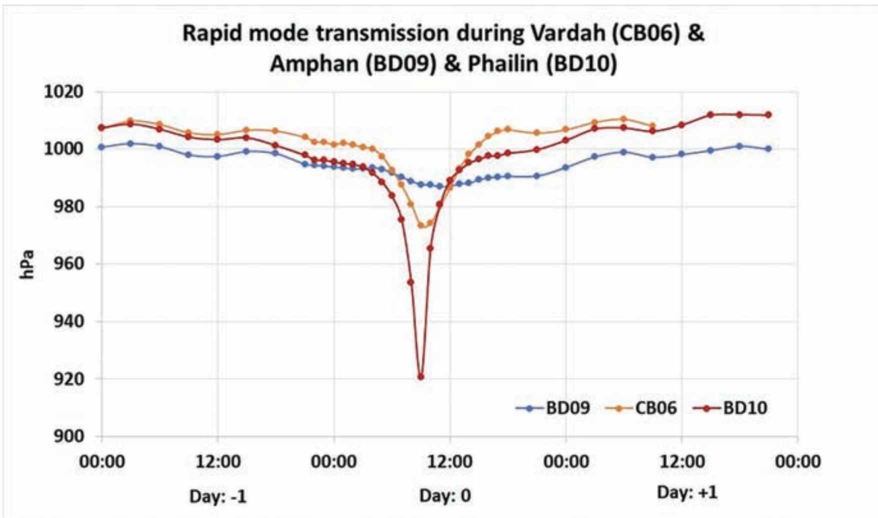
Modelling the Ocean-Atmosphere Energy Exchange (OAEE) using bulk-flux algorithms is a complex process that requires the measurement of incident solar radiation, outgoing long-wave radiation, sensible heat transfer by conduction and convection, and the latent heat released by the evaporation of ocean surface waters. The temperature difference between the surface water and the atmosphere is required for calculating the sensible heat flux, whereas the humidity gradient between the atmosphere and the ocean surface is used for computing the latent heat flux. Computations for long wave radiation also require surface temperature measurements (McPhaden et al., 2009).

Humidity sensors are based on thermal, resistive, and capacitive principles. The resistive-type humidity sensors use the ions in the salts to measure the electrical impedance of atoms. In the thermal types, two thermal sensors conduct electricity based on the humidity of the surrounding air. One sensor is encased in dry nitrogen whereas the other measures ambient air. The difference between the two sensor measurements gives the humidity. The capacitive-type with thin-film polymer sensor with capabilities shown in Table 3, consists of a substrate on which a thin film of polymer is deposited between two conductive electrodes. The sensing surface is coated with a porous metal electrode to protect it from contamination and exposure to condensation. The substrate is typically glass or ceramic. The thin-film polymer either absorbs or releases water vapor based on the increase or decrease in the relative humidity of the ambient air. The dielectric properties of the polymer film depend on the amount of absorbed water (Venkatesan et al., 2013).

As the relative humidity around the sensor changes, the dielectric properties of the polymer film change, and the capacitance of the sensor changes. The instrument's electronics measure the capacitance of the sensor and convert it into a humidity reading. The multiple plates have a un-

FIGURE 5

Air pressure recorded during passage of TC Phailin (16.3N/87.96E), Lehar (17.5N/89.12E), and Amphan (13.1N/80.31E).



ique profile that blocks direct and reflected solar radiation, but permits easy passage of air. The plate material is specially formulated for high reflectivity, low thermal conductivity, and maximum weather resistance. Based on 60 failures in 0.46 million offshore hours, the sensors are found to have an MTTF of 0.9 years. The upcoming developments in fiber-optic humidity sensors are expected to bring in new avenues in precision humidity measurements.

Wind Speed and Direction

Wind speed and direction are the key parameters for measuring ocean-atmosphere interactions for enabling monsoon and climate studies. Subsequent to the invention of the cup anemometer in the year 1846, anemometers based on hot-wire elements and ultrasonic technologies emerged. In rotary anemometers, the wind speed signals are generated using either a generator or a pulse generator, and the wind direction is measured using either a potentiometer or an encoder system. The propeller type anemometer has a sensor with a streamlined body and a vertical tail to detect wind direction. The threshold for these wind measurement sensors is around 1 m/s due to the mechanical friction associated with the generator. In these mechanical anemometers, the impellors and wind vane bearings tend to wear or corrode over time, which pose a challenge in the measurement of lower wind speeds and start-up speed thresholds. Bird landings in the sensor mounted in offshore MSB also hinder the measurements. The wind speed and direction measured by the anemometers in the buoy 16.5N/88 E during 2019 are plotted in Figure 6a. Based on 42 failures reported from the cup-type anemometers in 0.81 million offshore hours, the MTTF is 2.22 years.

The drawbacks in the rotary anemometers are overcome in the ultrasonic anemometers capable of measuring the wind speed based on the time-of-flight of sonic pulses between pairs of transducers, and hence have a very fine resolution, making them well-suited for turbulence measurements. A sonic anemometer has two pairs of sonic transmitting/receiving heads fixed facing each other across a specified span. The ultrasonic wave pulse signals are repeatedly emitted alternately from each pair of heads at certain time intervals. The propagation times of the ultrasonic pulses in the opposite directions are measured, from which the wind speed and direction are derived through vector synthesis. The main disadvantage is the distortion of the wind flow structure supporting the transducers and a lower accuracy caused during precipitation (Mathew et al., 2016). The threshold of these sensors is ideally zero as there is no mechanical friction. The capabilities of the cup anemometer are shown in Table 3.

Directional Wave Sensors

Wave data are vital for mariners, fishermen, offshore industries, weather forecasters, ocean engineers, harbor authorities, coastal managers, marine scientists, and the public-at-large for planning, coordinating, and conducting a variety of maritime activities. Ocean waves play a significant role in the OAEE and mixed layer dynamics. The wave characteristics have a significant impact on the coastal and shoreline dynamics. The wave measurements are normally done using MSB with a disc-shaped buoy hull (which acts as a primary wave sensing transducer) radially symmetric about the axis normal to the ocean surface. The motion reference unit (MRU) installed inside the hull is used to measure the motions in the linear and angular degrees of freedom, including the pitch, roll, heading, heave, surge, and sway. The vertical component of the acceleration measured using the

TABLE 3

Sensors' specifications.

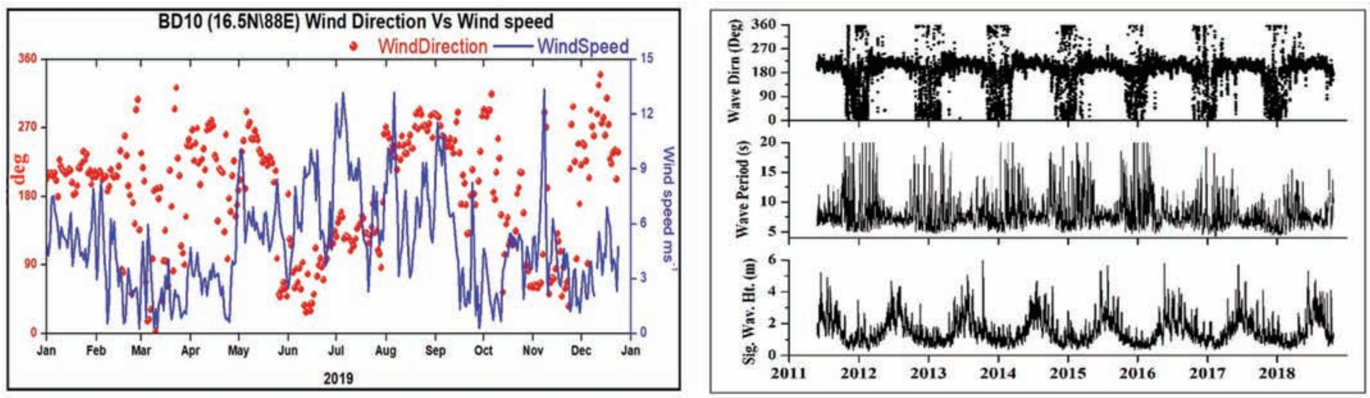
Measurement	Sensor Type	Make/Model	Resolution	Range	Accuracy
Wind speed	Cup	Lambrecht/1452	0.1 m s^{-1} (0.15 m s^{-1})	0-35 m s^{-1} (0–40 m s^{-1})	±2% FS (0.7 m/s at 35 m/s)
Wind direction	Wedge shaped wind vane	Lambrecht/1452	0.1° (1.4°)	0–359° (0–360°)	±1%
Air temperature	Pt-100 RTD	Rotronic Instrument Corp.: MP-101	(0.001°C)	-40...+60°C (15…+40°C)	±0.3°C
Relative humidity	Capacitance		(0.42 %RH)	0–100 %RH (0–110 %RH)	±1 %RH (5…95%RH) ±2 %RH (<5%,>95%RH)
Precipitation	Capacitance	R. M. Young: 50202	(0.05 mm)	0–50 mm (0–60 mm)	±1 mm
Downwelling shortwave radiation	Pyranometer	Eppley Laboratory: PSP-WHOI :in-built data logger	0.1 W m^{-2}	0–2,800 W m^{-2}	2 W m^{-2}
Downwelling longwave radiation	Pyrgeometer	Eppley Laboratory: PIR WHOI: in-built data logger	0.1 W m^{-2} 0.03°C	0 to 700 W m-2	2 W m^{-2}
Barometric pressure	Pressure transducer	Vaisala: PTB330	0.01 hPa (0.07 hPa)	500–1,100 hPa (800–1,100 hPa)	±0.07 hPa
Sea surface and subsurface temperature	Thermistor	Sea Bird Electronics: SBE37	0.0001°C (0.002°C)	–5 to +45 (0 to +35)	± 0.002 (-5 to 35 °C); ± 0.01 (35 to 45 °C)
Sea surface and subsurface conductivity	Conductivity cell	Sea Bird Electronics: SBE37	0.00001 mS m^{-1} (0.002 mS m^{-1})	0–7 S m^{-1} (2–7 S m^{-1})	±0.0003 S m^{-1}
Water pressure	Transducer	Sea Bird Electronics: SBE37	(0.002% of full range) (1,000 m) 0.003 bar	0–100 bar (0–60 bar)	± 0.1% of range (1,000 m)
Ocean current speed (single point)	Doppler Current Meter	Teledyne RD Instruments:DVS	1 mm s^{-1} (0.48 mm s^{-1})	±6 m s^{-1} (0–250 cm s^{-1})	1% of velocity ±0.5 cm s^{-1}
Ocean current speed (Profile)	Acoustic Doppler Current Profiler	Teledyne RD Instruments: 150/75 kHz	(1 mm s^{-1}) (0.48 mm s^{-1})	± 5 m/s (0–250 cm s^{-1})	± 1% ± 5 mm s^{-1}
Ocean max wave height	Gyroscope and accelerometer	Seatex:MRU 4	0.006% (0.019)	±20 m (0–20 m)	2% of range
Ocean peak wave period			0.1% (0.097 sec)	0–30 sec (0–25 sec)	±1%

accelerometers, is double-integrated to get the heave, which is the sea surface height. The fast-Fourier transform is used to obtain the wave spectra, which is done using an on-board processor (Venkatesan et al., 2016a).

The first wave measurement buoy was deployed by the Scripps Institution of Oceanography in 1974, which was capable of measuring the directional spectrum of 0.01–0.5 Hz ocean waves with an accuracy of 10% and an angular resolution of ~1° (McPhaden et al., 1998). The capabilities of the present MRUs used in MSB are shown in Table 3. The time-series observations of wave parameters in buoy (17.8N/89E) during

FIGURE 6

(a) Wind speed and direction during 2019 in the BoB. (b) Wave parameters recorded by NIOT buoy (17.8N/89E) during June 2011 to Dec 2018.



June 2011 to December 2018 are shown in Figure 6b. Based on 11 failures reported from the MRU in 0.74 million offshore hours, the MTTF is 10.1 years (Venkatesan et al., 2016b).

Precipitation

Precipitation has a significant influence in the upper ocean by reducing the salinity resulting in increased stratification. The restrained vertical mixing has a cascading effect by which the temperature and salinity could be further affected by reduced vertical mixing. Such stratification provides heat supply for the intensification of the tropical cyclones. Subsequent to the invention of the first standardized rain gauge in the year 1441 and the first tipping bucket rain gauge in the year 1662, the precipitation measuring instrument has improved in precision and reliability.

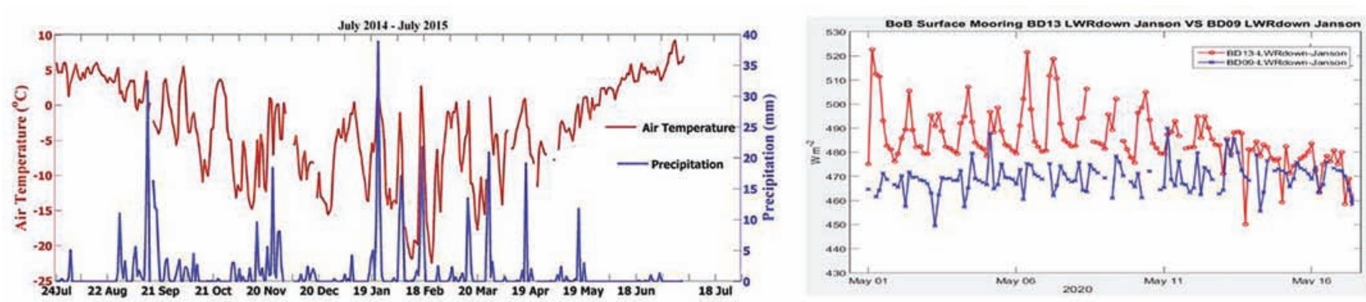
In recently developed precipitation instruments, rain or snow are collected in the catchment funnel and directed into the measuring chamber. The column level in the measuring chamber is sensed by a capacitive and converted to a linear voltage signal that can be read by external electronics. When the column level reaches a maximum, the instrument control system empties the chamber and the process repeats. The total precipitation is logged onboard by integrating the collected water quantities. They have self-contained thermostatically controlled heaters to allow operation under freezing temperatures (Gould, 2003). The current advanced precipitation sensors have a catchment area of 100–200 cm^2 and 0.001 mm/0.001 mm/h threshold. They have accuracies of ±0.1 mm or ±3% ±0.1 mm/min ±6 mm/h or ±3%. Based on 15 failures reported from 0.24 million offshore hours, the MTTF is 1.8 years. The temperature and the precipitation logged in a meteorological station in Ny-Alesund is shown in Figure 7a.

Solar Radiation

Modelling the complex OAEE using a bulk-flux algorithm requires precise measurement of the incident solar radiation and the outgoing

FIGURE 7

(a) Temperature and precipitation time series from meteorological station in Ny-Alesund. (b) Long wave radiation logged at 17.5N/89.12E (blue) and 13.95N/87E (red).



long-wave radiation. Approximately 99% of solar radiation is in the short wavelength region (0.3 to 3.0 μm), while longwave radiation is contained in the 3.5 to 50 μm region. The longwave radiation measurement sensors, called pyrgeometer, comprise the wire-wound thermopile detector with temperature compensation circuitry.

Short-wave radiation measurement sensors, called pyranometers, comprise a similar wire-wound thermopile detector coated with black lacquer (non-wavelength selective absorption). In pyranometers, isolation of the long-wave radiation from the short-wave solar radiation in daytime is accomplished by using a silicon dome. The inner surface of this hemispherical dome has a vacuum-deposited interference filter with a transmission range ~3.5–50 μm. When pyranometers are installed in a level horizontal plane, it is called the global shortwave irradiance sensor, and when positioned in a plane of a photo-voltaic array, is called the total irradiance sensor. When operated in an inverted manner, it measures the reflected or albedo irradiance. When it is shaded from the direct beam of the sun, it measures the diffuse shortwave irradiance. Precision thermistor with stable voltage reference senses detector temperature for applying temperature compensation (Srinivasa Kumar et al., 2016).

The long-wave radiation logged by buoys 17.5N/89E and 14N/87E during May 2020 is shown in Figure 7b. Based on 38 failures reported from 0.44 million offshore hours, the MTTF is ~1.4 years.

Water Depth

Water depth measurements are important for real-time tsunami monitoring in which the change in water level is measured in the deep-ocean for advance warning. The latest high resolution pressure sensor uses a very thin quartz crystal beam, electrically induced to vibrate at its lowest resonant mode. The oscillator is coupled to a bourdon tube, which is open at one end to the ocean so that the vibrating frequency is a function of the instantaneous pressure. The temperature data are used to compensate for the thermal effects on the pressure sensing element. The digital pressure sensor based on vibrating quartz crystal technology is highly stable and has measurement sensitivity better than 2×10^{-7} (<1 mm in 6,000 m water column).

Water Temperature and Conductivity

Sustained spatio-temporal measurements of the ocean subsurface temperature and salinity are essential for understanding the variability in the thermohaline and current structures on several timescales, which has important bearing on the evolution of seasonal monsoons and tropical cyclones. The parameters are used to compute the ocean heat content referenced as D26 isotherm and the salinity stratification in the near-surface waters, which have the potential to support the intensification of the tropical cyclones (Farahani et al., 2014). The first in-situ conductivity and temperature analyzer developed in 1964 is a turning point in the marine chemistry in which salinity is derived from conductivity measurement (Deyoung et al., 2019). Conductivity is a measure of the ability of the sea water to conduct electrical current and is measured by the sensor using a scale factor or cell constant that reflects the ratio of length and cross-sectional area of the sampled water volume in which the electrical current actually flows (Lin & Yang, 2020).

Biofouling is one of the major challenges in the long-term reliable operation of the conductivity-temperature (CT) sensors. Biofouling depends on the availability of nutrients due to upwelling, rate of vertical mixing, surface heat flux, associated regional dynamics, and stratification of the water column. Biofouling is predominant only down to a depth of 50 m and *Lepas anatifera* (common name, gooseneck barnacle) is the common biofoulant, irrespective of the location and water conductivity (Miloslavich et al., 2018). The average drift of conductivity measurements in the surface layer was very high; that is, 0.00335 and 0.00275 PSU/month in the Arabian Sea and the Bay of Bengal, respectively due to biofouling (Venkatesan et al., 2019).

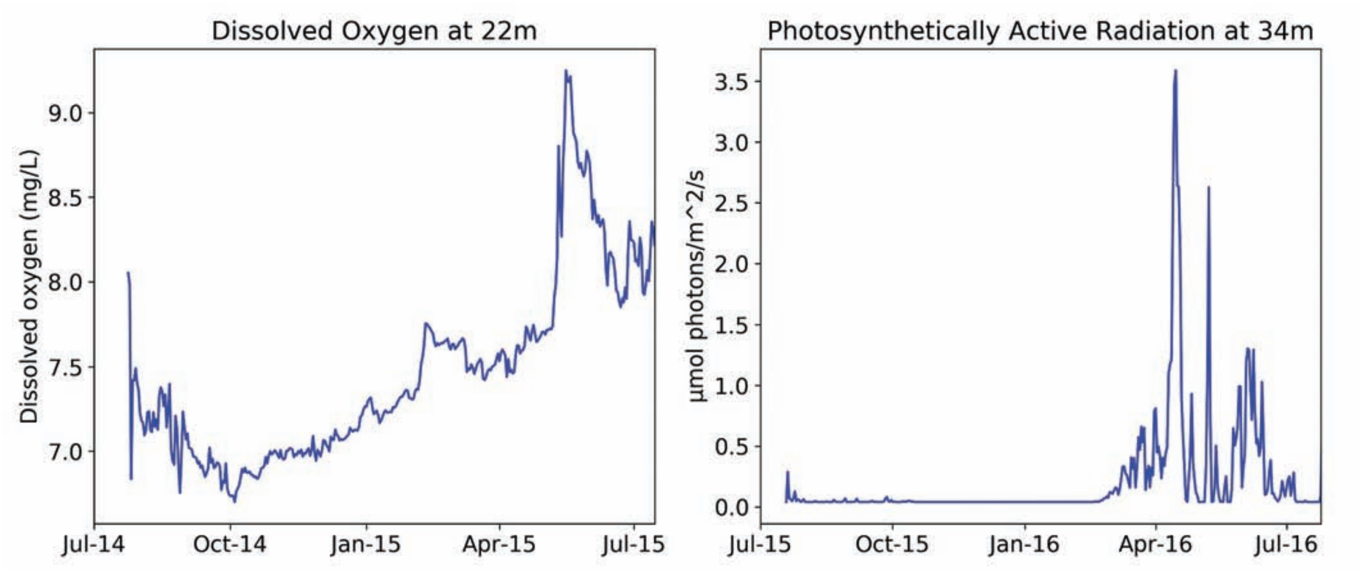
Sensor drifts indicate the need for reliable, eco-friendly, and cost-effective biofouling prevention mechanisms for obtaining quality data and reduced maintenance requirements. Usage of copper has shown significant reduction in marine fouling for long-term sensor deployments in coastal and open ocean environments and other less benign antifoulants (Figure 8b). A clean sensor head for long term in-situ oceanographic measurements is a big challenge to oceanographic research. At present, the MSB installable CT sensors have integrated inductive modems interfaces, internal batteries, memory, and optional pump for biofouling control designed for long-duration deployments on moorings. The capabilities of the CT sensors are shown in Table 3.

Seawater Velocity

Winds, water density, tides, and the spin of the earth drive ocean cur-

FIGURE 8

(a) DO, (b) annual PAR variation measured in the Arctic.



rents. Surface ocean currents are driven by the wind systems. The differences in water density, resulting from the variability of the water temperature, also cause ocean currents through thermohaline circulation. Ocean currents are an important abiotic factor that significantly influence food webs and reproduction of marine organisms and the marine ecosystems that they inhabit.

Water velocity measurement sensors work on the principle of the Doppler effect, which involves transmitting sound at a fixed frequency and measuring the backscatter. These sound scatterers are small particles or plankton that reflect the sound back to the transceiver. The Acoustic Doppler Current Profiler (ADCP) uses four beams to obtain velocity in three dimensions plus a redundant, which could vectorially resolve the other failed dimension. The Janus configuration is particularly good for rejecting errors in horizontal velocity caused by tilting (i.e., pitch and roll) of the ADCP. The capabilities of the DVS and ADCP are shown in Table 3.

Nitrate

Oceanic nitrate is the end product of the decomposition of the organic nitrogen, ammonia, and nitrite in successive stages. The concentration of the nitrate regulates the phytoplankton growth in the ocean. Nitrate concentration increases from 20 to 40 µm in 0 to 1,000 m water depths. In deeper waters, the stock of nitrate is linked to the volume of oxygen minimum zones, where bacteria may consume nitrate. Hence, in-situ time series measurements of nitrate in the ocean serves as inputs for monitoring water quality, early warning system of harmful algal bloom and for carrying out larger scale physiological modelling (Constable et al., 2016).

The in-situ nitrate measurement sensors are based on chemical-free optical technologies. The sensors use the ultra-violet (UV) absorption characteristics (at wavelengths of 217–240 nm) of the dissolved matter to measure in-situ concentration directly, without the need for reagents. The instruments comprise UV light source, fiber-optic sensing probe, precision spectrometer, and the onboard absorption curve-fitting algorithm using a lab-calibrated instrument-specific extinction coefficient for nitrogen and bromide to resolve the concentration of each. The instruments are designed to accurately measure absorption spectra with a resolution of 1 nm. The operating period is limited to ~900 h, which is the life of the deuterium lamp and has a power consumption of <10 W. At present, wiper systems are incorporated to keep the 10 mm gap free from biofouling. The capabilities of in-situ nitrate sensors are shown in Table 3.

Dissolved Oxygen

Measurement of DO determines the biological quality of water. In-situ DO sensors are based on galvanic and optical principles. The galvanic-type DO sensors consist of an anode and a cathode immersed in electrolytes inside the sensor body. An oxygen permeable membrane separates the anode and cathode from the water for which is the DO is to be measured. The permeable membrane allows oxygen from the sample water to diffuse into the sensor, where it is reduced at the cathode. This chemical reaction produces an electrical signal that travels from the cathode to the anode and then into the DO measuring instrument. Consumption of the oxygen at the cathode creates a pressure difference across the membrane that varies based on the partial pressure of oxygen in the sample. Therefore, as oxygen concentration increases, partial pressure and the rate of diffusion also increase, and the current to the instrument increases proportionally.

The optical-type DO sensors are based on a Stern-Volmer relationship, which is inversely proportional to luminescence lifetime in which the sensing element is a special dye that has luminance (red glow) when exposed to light of a particular wavelength. The dye is covered by an oxygen-permeable paint layer, which allows oxygen molecules to interact with the dye, while protecting it from other sample constituents. The oxygen interferes with the dye's luminescence (intensity and lifetime). The sensor emits light and measures the resultant luminescence with a photodiode. This reading is compared to a reference reading using the light of a different wavelength. A recent robust measurement technique that is immune to fouling and photobleaching uses a sine wave modulated excitation signal and measures the phase difference between the excitation sine wave and the received emission sine wave. The phase difference between the blue excitation and red emission shall be ~35 µs. The measurement and reference values are compared to calculate DO in the sample.

The response time of the optical oxygen sensors (7–10 s) are typically slower than electrochemical sensors (1–3 s). The response time of the optical oxygen sensors is less flow-dependent and does not require a continual flow of water past the sensor to measure properly. Optical DO sensors are ideal for long-term monitoring programs due to their minimal maintenance requirements. They can hold a calibration for several months and exhibit little calibration drift. At present DO sensors are capable of measuring in the range 0–450 µmol/kg in temperatures ranging from 0 to 30 degree and in salinities 0–35 psu and housed in pressure-rated enclosures for use up to 7,000 m water depth. The accuracy and resolution are ±3 and 0.2 µmol/kg, respectively. The data logged in the DO sensor in the Arctic during 2014 indicates higher DO due to the melting of the ice during summer season (Figure 8a).

Photosynthetically Active Radiation

PAR is the light of wavelengths ranging 400–700 nm utilized by sea plants for photosynthesis. The photosynthetic photon flux density is defined as the photon flux density of the PAR. There are two main types of sensors commonly used to measure underwater PAR, the planar and the scalar sensors. Planar sensors have a flat light collecting surface that responds to the light that impinges on their surface from downward directions. Planar sensors tend to underestimate the PAR because the collecting surface does not absorb upwelling radiation or light that reflects off the particles in the water. Scalar PAR sensors have a hemispherical or spherical collecting surface that functions to absorb light from 2π to 4π steradians. Most commercially available planar PAR sensors are cosine-corrected, which consists of a block of light-diffusing material that is designed to reduce errors associated with light impinging on the sensor surface from low incident angles. Modern PAR sensors have a range of 0–5,000 µmol photons/m2/s with a cosine error correction in the range 0–60° housed in enclosures for operation up to 7,000 m water depths. The PAR measurements made by the IndARC mooring indicates higher down-welling solar radiation during the summer months of the Arctic during the time increased ice melting and biological activity are observed (Figure 8b).

Turbidity and Chlorophyll

Phytoplankton constitutes the base of the aquatic food web and is a primary driver of the biogeochemical processes in the ocean. By using the light attenuation in the water column due to the scattering and absorption of the particles and molecules as a measure of water turbidity, the water quality can be related to a quantitative measurement for the light transmission capability. Waters with high turbidity levels are less transparent. An increase in turbidity in the ocean can be caused by the increase of total suspended matter, the increase of algal concentration in the water, and the increase of dissolved organic matter due to various atmosphere, ocean, and land processes.

As an indicator of water clarity, water turbidity can determine the thermal structure of the upper ocean and mixed layer dynamics. In addition, water turbidity can significantly impact the mixed layer dynamics and heat balance. The turbidity increase due to the increase in the concentration of the phytoplankton can lead to a significant enhancement of seasonal SST changes. An increase of the water turbidity due to phytoplankton biomass could lead to 20% amplification of the SST seasonal cycle after incorporating the derived absorption coefficient from ocean color satellite images into the ocean. Recent turbidity sensors have an operating range of 0–25 NTU and a sensitivity of 0.013 NTU; and chlorophyll sensors have an operating range and accuracy of 0–50 and 0.025 µg/l (Zeng & Li, 2015). The data logged by the turbidity and chlorophyll sensors in the NIOT Arctic sea during 2014 (Figures 9a and 9b) indicates higher DO due to the melting of the ice during summer season.

Data Quality Assurance

The moored buoy data are organized into a database and metadata are generated as per the ISO 19115 schema and data products are generated in NetCDF format as per the Ocean SITES standards and quality control procedures. Based on operational experiences, sensor data quality assurance is among the key strategies for increasing the availability of reliable data (Figure 10). The quality assurance program in place includes identification of appropriate sensors, periodic calibration, intercomparison, verification of the data quality during operations and immediately after deployments.

The Quality Assurance/Quality Control of Real-Time Oceanographic Data manuals issued by the U.S. Integrated Ocean Observing System and the data Quality Control Checks and Procedures issued by the National Data Buoy Centre are followed for quality control of the real-time data received from in-situ observations. These QC procedures are carried out in real-time and in delayed mode, known as Real Time Quality Control and Delayed Mode Quality Control. The MCC at NIOT is equipped with an in-house developed software ADvanced Data REception and analysiS System (ADDRESS), which features the facility to compare the outputs of similar sensors in closely located MSB during the same time period. The real-time quality control procedures involve checks for range, spikes, stuck value, impossible location, and impossible time. In the QC method, the measured values are checked against new range limits based on three times standard deviation of the climatological mean data, computed for each parameter, and specific to each location.

Subsequent to the field deployment, the functionality of the meteorological sensors is verified using the ship weather station. In order to ascertain the performance of the sea subsurface instruments, a twin-propeller electrically powered boat (ROB) capable of operating in the open-ocean with subsurface sensor string up to 4 knots speed is being developed and used. The ROB is equipped with an array of oceanographic sensors up to a depth of 10 m and real time video is transmitted to the vessel up to a range of 300 m, which was tested in the Bay of Bengal.

In order to ensure the quality of the meteorological sensor measurements, an inter-comparison method is followed and a standard reference platform is established to evaluate

FIGURE 9

(a) Turbidity, (b) chlorophyll measured in the Arctic.

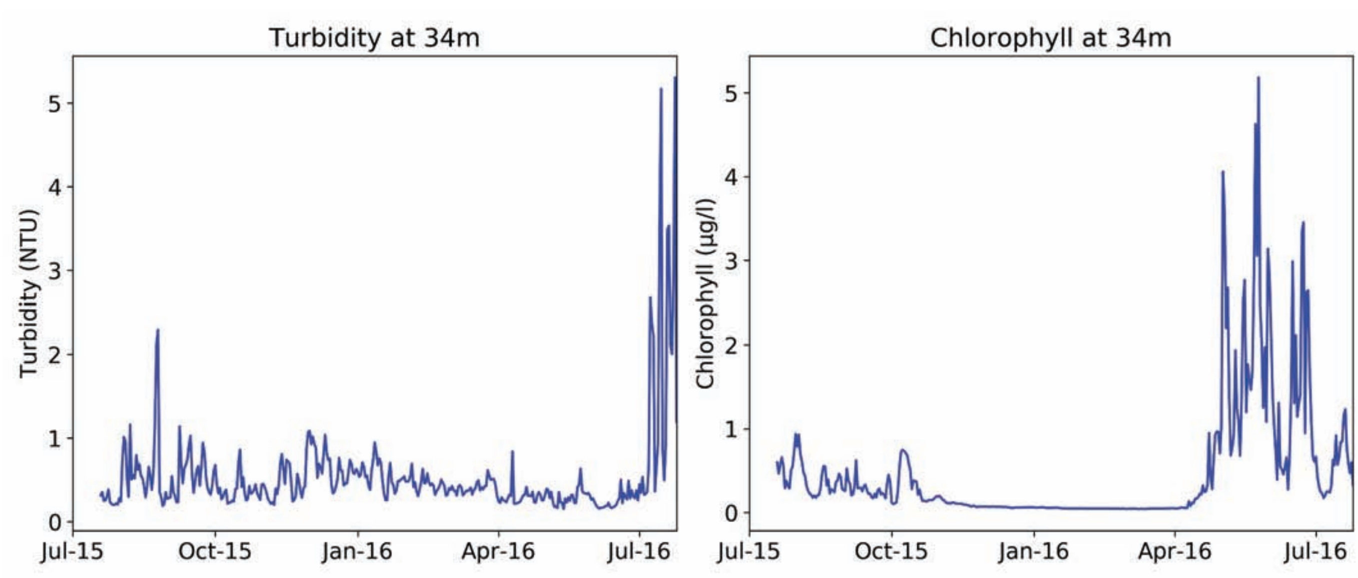
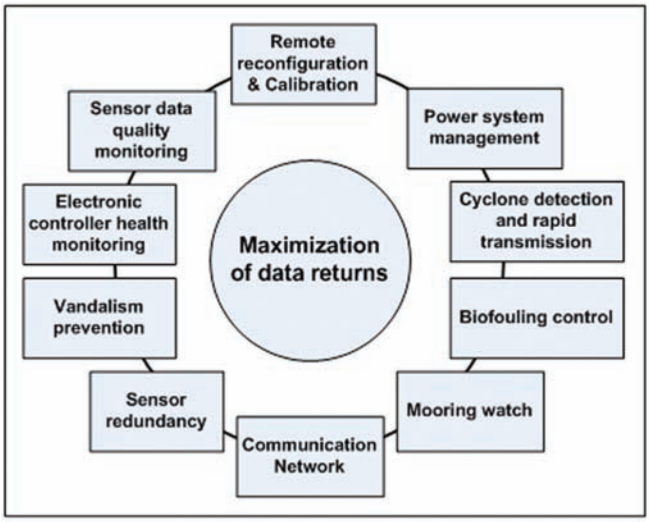


FIGURE 10

Methodologies adopted in increasing MSB data returns.



and compare the long-term performance of different make data loggers (IDAS/NIOT, GENI/FUGRO OCEANOR, and Campbell USA). In order to ensure that the sensors perform within the accuracy limits, post-retrieval checks are conducted to quantify the drift in the sensor over the deployed period and to derive the coefficients required for error correction. For this purpose, a Calibration Test Facility (CTF) with reference standard instruments is established based on the recommendations of the Regional Marine Instrumentation Centre (RMIC). These reference standard instruments linked with recognized National/International standard and the CTF follows the guidelines suggested by the IEC 17025.

Considering the importance of standards and calibration for EOVs and related capacity building requirements the WMO and UNESCO's IOC have jointly undertaken an effort to establish WMO-IOC RMIC. The RMICs are expected to facilitate adherence of observational data, metadata, and processed observational products to higher level standards for instruments and methods of observation, by providing facilities for the calibration and maintenance of marine instruments and the monitoring of instrument performance and assistance for instrument intercomparisons, as well as appropriate training facilities. RMIC facilities are currently established at the National Data Buoy Centre of NOAA in the United States and at the National Centre of Ocean Standards and Metrology of SOA in Tianjin, China. These systematic procedures are adopted to ensure quality data is shared with users.

Conclusions

This article describes the importance of in-situ oceanographic and meteorological sensors in carrying out effective assessment of ocean ecosystem and for societal benefits. The technological trend with reference to principle of operation, sensor drift, energy consumption, and the sensitiveness of oceanographic sensors to bio-fouling are explained in detail. Cost effective in-situ sensors are essential to fulfill the long-term goal of the UN Decade of Ocean Sciences for Sustainable Development in building strategic global ocean observing systems. Futuristic technology should look for multiple platforms capable of self-calibration, extended deployment periods, and be equipped with AI-enabled low-power sensors. We conclude that sustained high-quality EOV-based ocean observation plays a foundational role in documenting the state and variability of components of the climate system and facilitating climate prediction required for a clean, resilient, productive, safe, well-observed, documented, and predicted ocean. Finally, the challenges associated with sustaining these observations over long timeframes are an important factor to be addressed in this UN Decade at the national, regional, and global level.

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PAPER

A Web-GIS and Mobile-Based Application for a Safe Ocean for Fishers

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ABSTRACT

One of the societal outcomes envisaged for the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) is a safe ocean where the safety of operations at sea and the coast are ensured. The Indian coast is prone to tropical cyclones, and the recent Ockhi, Gaja, Nilam, and Nivar cyclones devastated coastal Tamil Nadu in southern India, particularly the fishing community. This brought into focus the need to develop tools for the safety of fishermen at sea. A user-friendly application was developed named "Thoondil" (meaning fishing rod in the local language) by the National Centre for Coastal Research and made operational by the Department of Fisheries, Government of Tamil Nadu. It comprises a web-GIS-based dashboard for the state administrators and an android application for the fishermen. The salient features of the mobile application include the compass, weather, rescue plan, offline maps that provide the route to the nearest ports, incidence reporting, weather details, and potential fishing zone. The Thoondil dashboard provides information about the users and travel details, and helps to get information about the fishermen at sea at any point of time. A two-way communication between the administrators and the fishing community is enabled. The system is available in vernacular language with more than 15,000 downloads in a couple of months. Based on user interactions, it has evolved as a pan-India application and currently replicated in Kozhikode, Kerala. The use of the app has reduced risk to the fishing community, especially during hazards and has also contributed to the resilience of the coastal fishing communities.
Keywords: Thoondil, offline maps, SOS, web-GIS dashboard

Abbreviations
UN—United Nations
GIS—Geographical Information System
SOS—Save Our Souls
GPS—Geographical Position System
IoT—Internet of Things
IMD—Indian Meteorological Department
PFZ—Potential Fishing Zone
INCOIS—Indian National Centre for Ocean Information Services
ISRO—Indian Space Research Organization
NavIC—Navigation with Indian Constellation
NCCR—National Centre for Coastal Research
FTP—File Transfer Protocol
OTP—One time password
GUI—Graphical User Interface
OS—Operating system
MoES—Ministry of Earth Sciences
SMS—Short Message Service

Introduction

About 7 million people living along the Indian coastline, spanning over 8,100 km (Chakraborty et al., 2019), depend upon fishing for livelihood. But fishing has many uncertainties and risks as fishermen receive no formal safety training and their work environments change seasonally due to the weather (McDonald & Kucera, 2007). Most accidents at sea are part of daily operations, with a substantial nexus with weather and sea conditions with sudden variation and uncertainties. Rising wind, strong currents, high waves, and low visibility due to the weather make fishing during the monsoon season extremely dangerous, especially at night. Some of the risks include getting lost at sea, being driven to far-off locations by strong currents, and accidents such as boats capsizing and even lives lost during inclement weather conditions. Other risks include collision with ships, being run over by fishing nets, and aborted trips in extreme weather after burning a lot of fuel (Karthikeyan et al., 2012). In general, fishermen must strive hard and face a variety of risks for effective fish harvesting (Amrita & Karthickumar, 2016).

Most of the boats have not installed GPS and echo sounders that can enhance personal safety for fishermen at sea (Rodrigues & Kiran, 2013), which results in clashes due to trans-border fishing, especially in the Indo-Sri Lankan border (Viji et al., 2017). Many cases are reported where the fishermen accidentally cross the border leading to losses in both human lives and their economic incomes (Arunvijay & Yuvaraj, 2014). None of the present GPS systems satisfies civilian navigation safety requirements in the sea, and a need to provide an alert when fishers cross another country's border was realized (Rahman, 2014).

Fishermen need the weather information on ocean variables like surface temperature, wind direction, wind speed, wave movement, and rainfall before coming onboard. The importance of weather information is clear from the Ockhi cyclone that affected nearly 100 fishing villages across Tamil Nadu and Kerala. The cyclone caused the death and disappearance of more than 350 people, most of them fishermen between November 30 and December 3, 2017. The loss of many fishermen was mainly due to a lack of navigation and security features during the voyage. Hence, there is a need to implement facilities for reducing human and material loss (Darshan et al., 2014).

Applications developed for the fishing community aim to close the gap between data deficiency, effective fisheries management, effective fish harvesting, and communication, especially during times of hazards, and reduce overhead costs and serve as useful disaster risk-reduction tools. Incidentally, they also motivate fishermen to assimilate the technological growth occurring worldwide. A user-friendly, multi-language mobile application for the fishing community was needed (Amrita & Karthickumar 2016). An IoT-based nautical monitoring system was proposed for country border identification (Jothilingam & Glindis, 2018). Some of the mobile applications currently used by fishermen across the globe are:

- Fishing Points—combines features like GPS navigation, optimal fishing times, tidal prediction, weather forecast, and map functionality (https://play.google.com/store/apps/details?id=com.gregacucnik.fishingpoints&hl=en).
- The Fishing & Hunting—uses solunar table theory and offers optimal fishing times (https://play.google.com/store/apps/details?id=com.antonnikitin.solunarforecast&hl=en).
- The Fish Brain—features include fishing forecast, exploring new fishing locations, check exact catch position, and also follow your friends fishing (https://play.google.com/store/apps/details?id=com.fishbrain.app&hl=en).
- The Fish Hunter-Pro—provides advanced GPS tracking and mapping, logbook on catches, a hardware device for finding fishes, and fishing trip crucial planning toolkit (http://www.fishhunter.com/pro/).
- Deeper Smart Fish Finder—features options like find fish, depth, temperature, reveal new spots and potential fishing zones, catch, and share (https://play.google.com/store/apps/details?id = com.fridaylab.deeper&hl=en).
- SONARBall—similar to Deeper Smart Fish Finder, offers fish view, sonar view, water temperature, water depth; analyzes the environment and increase the catches, and detects the potential fishing zones (https://play.google.com/store/apps/details?id=jp.co.h2works.sonarball.activity&hl=en).

Many mobile application of a similar type are available for fishers. Unfortunately, there are no such applications in India that combine every need for fishermen in one mobile application. With mobile apps integrated into everyday life, there is a need for the fisheries sector to partner with information technology providers and produce sustainable solutions using mobile apps (Sharma & Dhenuvakonda, 2019).

Security of life and livelihood is an integral part of any development process. A "support-led strategy" achieving higher growth in fisheries with a concern for fisher-folk can yield rich social benefits in terms of avoiding loss of lives and material at sea especially during storms and cyclones by communicating timely warnings from the meteorological department and authorities and vice versa. A judicious blend of both promotional and protective measures is needed (Suresh et al., 2018).

As a first initiative, the National Centre for Coastal Research (NCCR) under the Ministry of Earth Sciences and Department of Fisheries, Government of Tamil Nadu developed "Thoondil: A web-GIS-based decision support system for the safety and security of the Fishermen in Tamil Nadu". *Thoondil* means a fishing rod in Tamil, and is an application developed with available user-friendly technology benefiting both the fishing community and the state administrators, specifically during hazard mitigation and management operations.

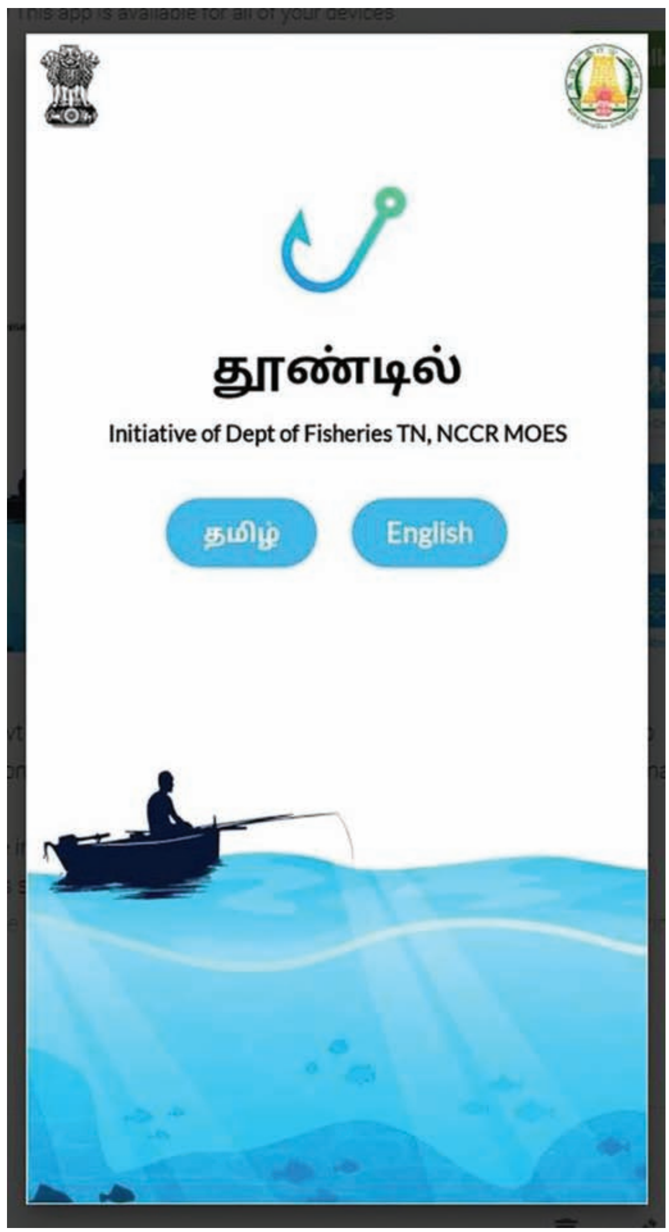
Thoondil was developed with weather inputs from the Indian Meteorological Department (IMD) and Potential Fishing Zone (PFZ) from the Indian National Centre for Ocean Information Services (INCOIS) and is a web-GIS-based dashboard and mobile application designed exclusively for administrators and fishing community in English and vernacular language (Tamil) as shown in Figure 1.

The web dashboard is for the state administrators to overview the state's fishing operations at any point of time, while the app is mobile-based and exclusively for the fishermen at sea. This android-based mobile application helps fishermen navigate the sea, find probable fish potential zones, and alert them during storms. Two-way communication between the authorities and fishermen is possible through the mobile application within the network coverage area of 12 nautical miles. The system was tested multiple times before it was made available to users through the Google Play Store.

Thoondil encompasses several fishermen-friendly features such as weather information from IMD, route information, boundary alerts, offline maps that work even when there is no Internet connectivity, PFZ information from INCOIS, and emergency contact capability in times of distress, such as report reporting using geo-tagged photos, etc. The dashboard installed in the department of fisheries provides administrators with information for effective mitigation and planning, especially during hazards. Thoondil has an interface to shift to vernacular language. At present, Thoondil is bound by the limitation of the mobile network coverage area. However, efforts are on to extend it to offshore areas through Indian Space Research

FIGURE 1

The Thoondil mobile application is available in both English and Tamil languages for the state of Tamil Nadu. The Tamil version of the application is shown here.



Organization's NavIC (Navigation with Indian Constellation).

Application Framework

The framework provides structure and behavior, mainly to support context-based activity schedule composition, through a process known as trail generation, identifying whether or not schedule reordering is required following context change and implementing subsequent automatic schedule reordering as appropriate. The framework mainly supports the development of trails-based applications in a generic, extensible manner, enabling developers to reuse common application components and extend the framework to support application-specific behavior (Driver & Clarke, 2008).

The application is built upon the fisherman's name, registered phone number, and boat details available at the department of fisheries, Tamil Nadu. This data forms the data layer, which is synced to the mobile data storage, as shown in Figure 2. The Presentation layer consists of separate layers for the fishermen and the administrator. The mobile application installed from the registered fisherman's mobile number is verified using a randomly generated one time password (OTP). Further, the fishermen can log in into the application upon the verification of OTP. The fisherman in his mobile application has the ability to register his mobile number along with the boat details as a new user into the mobile application using the registered mobile number and boat number. Further, a user dashboard with a host of features like weather, PFZ, incidence reporting, etc., is available. The administrator dashboard gives an overview of the fishing activity across the sea. The user dashboard is visible on successful login into the application—the Administrator logs in to his web dashboard after verification of user ID and password.

Web services like the weather data from IMD and PFZ data from INCOIS are transferred into the NCCR server application. The other GIS layers, including the location information, maps, and notifications, are available. Together, they form the application layer of the system. The application layer is available for both the Administrator and the fishermen.

FIGURE 2

Process flow chart for Thoondil.

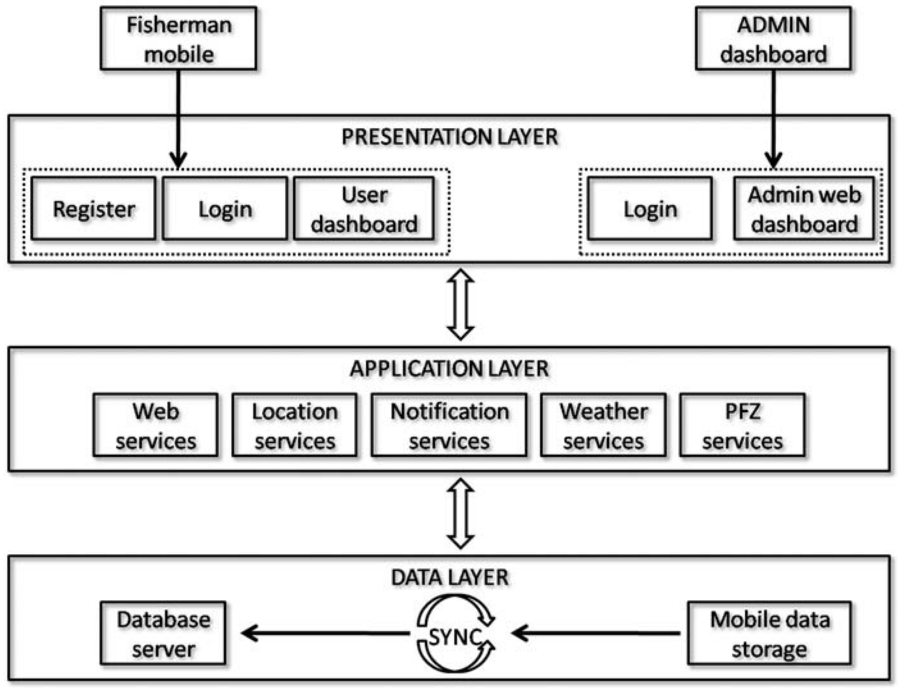


FIGURE 3

Thoondil mobile app and features.

Discussion

Thoondil is the first of its kind web-GIS-based decision support system to help fishermen and administrators especially during times of hazards. The system's simple design makes it user-friendly for fishermen and an efficient tool for disaster mitigation. The design of the system is to aid fishermen from the start to the end of a trip, combining information like weather warnings, a potential area of fish abundance, and help in navigating through the sea. Fishers can report any unprecedented events at sea with geo-tagged images. The mobile app and dashboard ensure two-way communication between fishermen and authorities.

Mobile Application Design

The fisherman's details, including the registered boat number, name, and type of boat are available with the fisheries department of Tamil Nadu and stored in the NCCR server. Any new update in the fisherman data will refurbish in the NCCR server. The app is built upon this data.

The mobile app consists of features (Figure 3) designed to suit the needs of the fishermen without compromising their safety. Weather data includes temperature, rainfall, humidity, sunrise, sunset, moonrise, and moonset pertaining to each location and corresponding time from the IMD under the Ministry of Earth Sciences, and PFV data from INCOIS, under the Ministry of Earth Sciences are transferred to the NCCR server regularly through FTP services provided by the respective institutes. The weather reports are updated daily by IMD and reflected in the web dashboard and mobile application (Figure 4a). Any weather warnings from IMD are communicated both to the administrators and fishermen at sea through the mobile app and web dashboard. The Save Our Souls (SOS) or distress button transfers the boat coordinates and fisherman's details travelling in the boat to the administrator for an effective rescue operation. Geo-tagged images captured by the fishermen using the report incident option are reflected immediately in the admin dashboard (Figure 4b).

Thoondil uses the registered boat information provided by the department of fisheries to verify the user's authenticity using two fields, namely, the boat number and the district of registrations. The other fields are picked up by default from the database, and OTP verification ensures the validity of the user's phone number. Before venturing into the sea, the registered user, usually the boat owner, should add his crew's details, assign the driver for the trip, and then de-

FIGURE 4

(a) Weather information from IMD. (b) Incident reporting feature for fishermen.

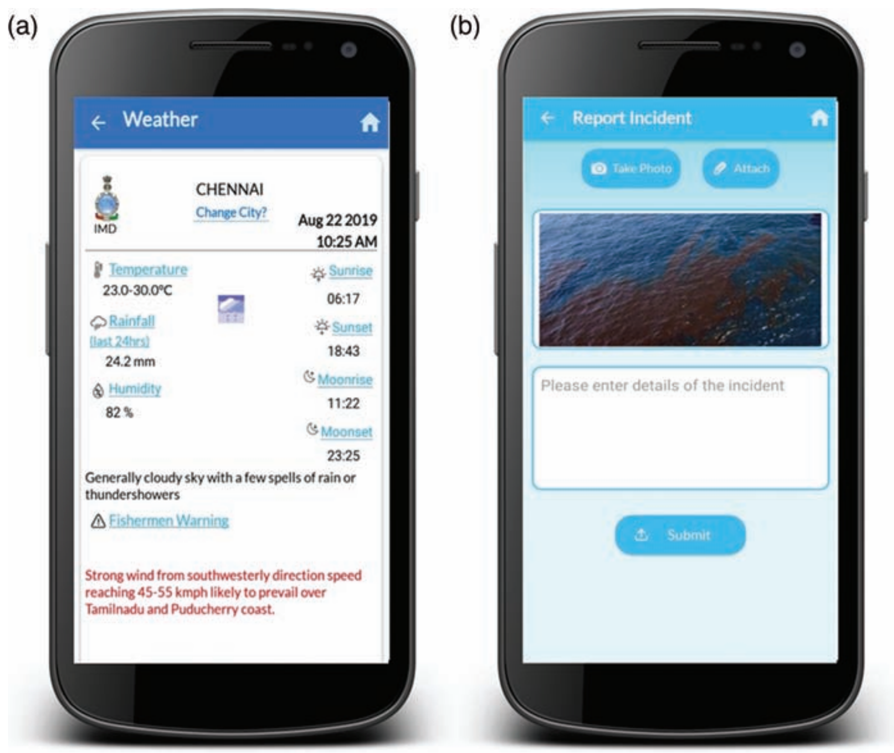
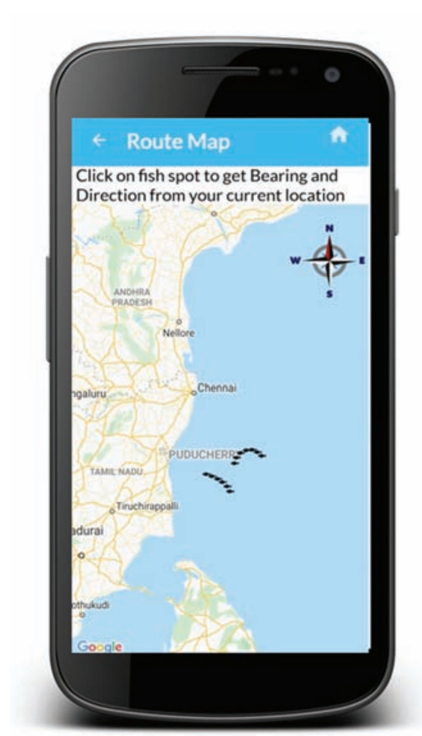


FIGURE 5

Potential fishing zone in map format.



clare the trip. The first level of information enables access to a host of features incorporated in the app.

The Location Information enables the fishermen to know the map's current location, the bearing, speed, and distance travelled from shore. The Drop Pin option saves sites of interest for future use. Offline maps are used throughout the application to facilitate fisherman to access maps even beyond the network coverage area.

PFZ information from INCOIS provided in the form of a map shows locations for possible fish abundance. The salient feature of this app is that the PFZ information provided with reference to predefined landing centers is converted such that the bearing and directions of the locations are shown with reference to the current locations of the fishermen (Figure 5).

The emergency escape route information feature gives information on the nearest port, which could be very useful during calamities. Coordinates of the nearest port with distance, bearing, and direction from the fisherman's current location will be shown on the map. The fisherman can also select alternate locations and new bearing and direction are calculated and displayed. The fisherman will also receive SOS from Administrators sent from the Fisheries Department through SMS and vice versa. The fisherman's distress message will be forwarded with his location to aid in the mitigation operation.

The IoT device (Figure 6) fitted with emergency SIM receives SOS messages when received from the Thoondil App and alerts the district authorities with a loud alarm. It also displays details of the sender, his boat number, and location of the incident on the map. Further, taking into consideration the availability of network connection between the fisherman and the administrator during a calamity, the mobile application is currently being integrated with the NaVIC system, which ensures an uninterrupted two-way communication using the Indian satellite. In NaVIC system, two-way communication between fishermen at sea and administrators is enabled through Indian satellites through a small device installed in the fishing vessel. The application will be provided with an option to communicate with the administrators on land through a satellite-enabled communication path. The location of the boat can be easily identified using this system for speedy rescue and recovery operations.

Web-GIS-Based Dashboard

The dashboard's aim is for the state administrators to get an overview of the fishing operations in the state at any point in time. The admin dashboard is a web-GIS-based portal (Figure 7) that helps the administrators keep track of the state's fishing activity. An online dashboard is

FIGURE 6

IoT device for SOS feature.

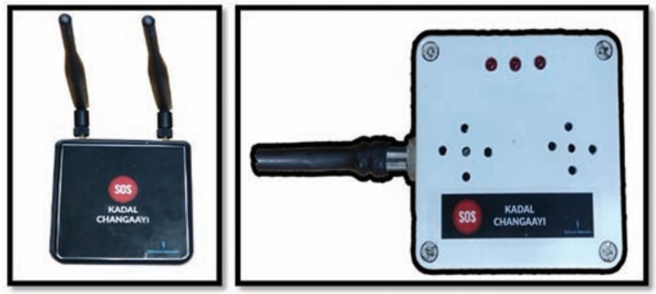
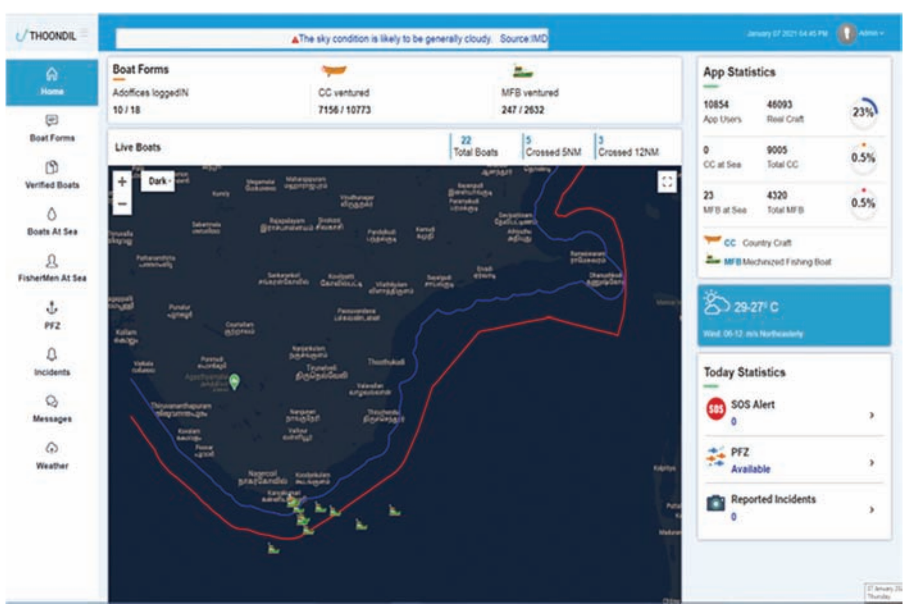


FIGURE 7

Thoondil WebGIS dashboard.



made available in the Department of Fisheries office wherein the administrator would be able to keep track of the state's fishing activity. The information on the boats at sea and the number of men at sea at any given point of time is made available. The administrator can monitor their course and broadcast messages to them, such as weather warnings.

The decision support system is built to enable queries related to the type of boats, the number of boats in a district, the distance of vessels from the shore, date and time of operations, etc. Provision has also been made to see the number of boats within 5 nautical miles, 12 nautical miles, etc., and boats nearing the international boundary line near Sri Lanka can also be alerted in advance. This information is also provided to all administrators in the form of charts and tables.

BETA Testing

Testing of the mobile application was done to check its functionality, usability, and consistency (Nimbalkar, 2013). Testing determines the performance and reliability of mobile applications, which strongly depends on the mobile device resources, the device operational mode, the connectivity quality and variability, and other contextual information. Memory leaks may limit the memory resource and active processes and may reduce the device battery. An idea can be to automatically execute scripts captured during the user interaction, which can be replayed and modified even on different devices and lead to graphical user interface failure. Testing an application on a multitude of mobile devices is undoubtedly an important challenge, especially in the Android operating system (OS), where different mobile phones provide additional features and hardware components, and phone manufacturers may significantly customize the OS (Muccini et al., 2012).

The testing of the Thoondil application on both a mobile and a web-GIS dashboard was done multiple times by the NCCR team and the fisheries department of Tamil Nadu. The local fishermen, the officers from the Department of Fisheries, and a scientist from the NCCR were involved in testing the application. The fishermen's feedback was obtained and incorporated in the application, and multiple testings were done before uploading the operational version (Figure 8).

This application currently makes use of smartphones and hence works only up to data network coverage areas, which are roughly up 12 nautical miles depending on the type of mobile network and network provider. However, SMS text messages services will be available even beyond that limit, based on the availability of the network coverage area. Efforts are on to link the application with a satellite device that will enable the system to work beyond network coverage areas. The system will also be updated for a two-way communication with the nearest fishing vessel at the time of emergency and extend the scope of the system beyond Android-based mobile phones. The system will incorporate the port details and its conditions in case of calamities by working together with the respective authorities.

FIGURE 8

Thoondil training for administrators.

Conclusions

The Thoondil application developed in the vernacular language for the Tamil Nadu Coast in southern India is a viable and cost-effective solution to address the safety and security of fishermen at sea in this part of the country. The Thoondil application was made available for fisherman free of cost, and its simple design and user-friendly features make it a very user-friendly application among the fishing community. It also addresses decision makers' requirements and provides all required information about the fishermen at sea for effective decision making. However, at present it works only up to the network coverage area and efforts are on to extend it to the offshore regions. Thoondil is a low-cost, user-friendly application with multiple features developed in-house to contribute to a safe ocean, especially for the fishing community in this part of the country and can be replicated across coastal India.

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Inspiring U.S. Contributions to the UN Ocean Decade: The U.S. National Committee and Ocean-Shots

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With the ringing in of the New Year of 2021 came the start of the United Nations Decade of Ocean Science for Sustainable Development (https://www.oceandecade.org/). The Decade represents the recognition, at highest government levels, of the critical role that healthy and productive oceans play in sustaining lives and supporting economic well-being, and that a concerted scientific effort is necessary to mitigate the myriad threats to oceans. To the ocean science and engineering communities, The Decade presents a framework under which they can establish new partnerships with policy makers, local communities, businesses, and non-governmental organizations (NGOs) to design more inclusive approaches for marine research and engineering—an important element for building a sustainable Blue Economy and for managing our oceans to benefit humanity. In this context, it also offers the opportunity to develop bold new approaches to marine science in support of sustainable development. In the words of The Decade Implementation Plan (https://www.oceandecade.org/resource/108/Version-20-of-the-Ocean-Decade-Implementation-Plan-), these efforts should create "the science we need for the ocean we want," leading to "the ocean we need for the future we want."

A key component of the structure of The Decade is the establishment of national committees, designed to act as interfaces between national efforts and the UN Decade as well as offer a level of national coordination for Decade-related activities. In November 2019, former MTS Board Member Craig McLean, U.S. representative to the Intergovernmental Oceanographic Commission and a member of the Executive Planning Group for the UN Decade, approached the National Academies of Science, Engineering and Medicine (NASEM) to host a U.S. national committee, one of the first, if not the first, national committee to be established. In the spring of 2020, NASEM appointed the U.S. National Committee (USNC), built around the Ocean Studies Board, which advises the NASEM on ocean science and policy, with the addition of several key representatives from other NASEM units with overlapping intersts. Recognizing the decade-long scope of its efforts and the valuable perspectives of young scientists just embarking on ocean careers, NASEM appointed four Early Career Liaisons to augment the membership of the committee. Looking even further to the future, the USNC is also coordinating with a Youth Advisory Council, representing a remarkable group of enthusiastic and engaged youth ranging from 14 to 25 years old (https://h2oo.org/us-yac-for-un-ocean-decade/). As one of the first national committees to be established, the USNC has developed a program of activities to enable routine, cross-sectoral coordination within the United States on Decade initiatives. The Committee plays a central communications role, informing the U.S. ocean community about The Decade, providing a venue for the exchange of information about Decade events and initiatives, and tracking various national and international Decade-related activities. This has been accomplished through the creation of the Ocean Decade U.S. website (https://www.nationalacademies.org/our-work/us-national-committee-on-ocean-science-for-sustainable-development-2021-2030) and the initiation of Ocean Decade U.S. Nexus, an expanding network of U.S. organizations that share information and communicate news about U.S. efforts related to The Decade. Industry is a key partner in Decade activities; the Marine Technology Society is a member of the Nexus and we encourage MTS members to consider joining the Nexus to share their Decade-related activities and participate in Ocean Decade U.S. meetings and activities.

Importantly, the USNC has sought not only to engage, but also to challenge the community to seize the opportunity of The Decade and think about bold, creative, and audacious new ways to advance marine science in support of sustainable development. With this in mind, the Committee issued a call for "Ocean-Shots: *ambitious, transformational research concepts that draw inspiration and expertise from multiple disciplines and fundamentally advance ocean science for sustainable development*." The Committee seeks to foster creation of programs of such broad-reaching scale and relevance that they capture the imagination of the science community, the public, research sponsors, and policy makers, much like the moonshot of the 1960s.

In the call for Ocean-Shots, we offered a series of criteria for the submissions. These included directly addressing at least one of the ten "Challenges" set forth in the UN Ocean Decade's Implementation Plan (see box), demonstrating potential transformative impact, engaging scientific, technical, and other sectors outside the traditional ocean sciences, building capacity and a cadre of next-generation ocean scientists, and demonstrating opportunities for international participation and collaboration. The response to the call was remarkable, with over 100 submissions. The Ocean-Shots were the main feature for the Ocean Decade U.S. Launch Meeting held (virtually, of course) on 3-4 February, 2021. At this meeting (which had more than 1,200 people registered), over 80 Ocean-Shots were presented in the virtual poster session (posters available at: https://www.nationalacademies.org/our-work/us-national-committee-on-ocean-science-for-sustainable-development-2021-2030/ocean-shot-directory). In addition, eight Ocean-Shots were featured in the plenary sessions to present a variety of challenges and illustrate elements of exciting, innovative, and relevant areas of research for the subsequent discussion sessions.

UN Decade Challenges

- **Challenge 1**: Understand and map land and sea-based sources of pollutants and contaminants and their potential impacts on human health and ocean ecosystems, and develop solutions to remove or mitigate them.
- **Challenge 2**: Understand the effects of multiple stressors on ocean ecosystems, and develop solutions to monitor, protect, manage and restore ecosystems and their biodiversity under changing environmental, social, and climate conditions.
- **Challenge 3**: Generate knowledge, support innovation, and develop solutions to optimize the role of the ocean in sustainably feeding the world's population under changing environmental, social, and climate conditions.
- **Challenge 4**: Generate knowledge, support innovation, and develop solutions for equitable and sustainable development of the ocean economy under changing environmental, social, and climate conditions.
- **Challenge 5**: Enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt, and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the ocean, climate, and weather.
- **Challenge 6**: Enhance multi-hazard early warning services for all geophysical, ecological, biological, weather, climate, and anthropogenic-related ocean and coastal hazards, and mainstream community preparedness and resilience.
- **Challenge 7**: Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely, and actionable data and information to all users.
- **Challenge 8**: Through multi-stakeholder collaboration, develop a comprehensive digital representation of the ocean, including a dynamic ocean map, which provides free and open access for exploring, discovering, and visualizing past, current, and future ocean conditions in a manner relevant to diverse stakeholders.
- **Challenge 9**: Ensure comprehensive capacity development and equitable access to data, information, knowledge, and technology across all aspects of ocean science and for all stakeholders.
- **Challenge 10**: Ensure that the multiple values and services of the ocean for human well-being, culture, and sustainable development are widely understood, and identify and overcome barriers to behavior change required for a step change in humanity's relationship with the ocean.

UN Decade Outcomes

Outcome 1: A clean ocean where sources of pollution are identified and reduced or removed. Society generates a vast range of pollutants and contaminants including marine debris, plastic, excess nutrients, anthropogenic underwater noise, hazardous chemicals, organic toxins, and heavy metals. These pollutants and contaminants derive from a wide variety of land- and sea-based sources, including point and non-point sources. The resulting pollution is unsustainable for the ocean and jeopardizes ecosystems, human health, and livelihoods. It will be critical to fill urgent knowledge gaps and generate priority interdisciplinary and co-produced knowledge on the causes and sources of pollution and its effects on ecosystems and human health. This knowledge will underpin solutions codesigned by multiple stakeholders to eliminate pollution at the source, mitigate harmful activities, remove pollutants from the ocean, and support the transition of society into a circular economy.

Outcome 2: A healthy and resilient ocean where marine ecosystems are understood, protected, restored, and managed. Degradation of marine ecosystems is accelerating due to unsustainable activities on land and in the ocean. To sustainably manage, protect, or restore marine and coastal ecosystems, priority knowledge gaps of ecosystems, and their reactions to multiple stressors, need to be filled. This is particularly true where multiple human stressors interact with climate change, including acidification and temperature increase. Such knowledge is important to develop tools to implement management frameworks that build resilience, recognize thresholds and avoid ecological tipping points, and thus ensure ecosystem functioning and continued delivery of ecosystem services for the health and well-being of society and the planet as a whole.

Outcome 3: A productive ocean supporting sustainable food supply and a sustainable ocean economy. The ocean is the foundation for future global economic development and human health and well-being, including food security and secure livelihoods for hundreds of millions of the world's poorest people. Knowledge and tools to support the recovery of wild fish stocks, deploy sustainable fisheries management practices, and support the sustainable expansion of aquaculture, while protecting essential biodiversity and ecosystems, will be essential. The ocean also provides essential goods and services to a wide range of established and emerging industries including extractive industries, energy, tourism, transport, and pharmaceutical industries. Each of these sectors has specific, priority needs in terms of increased knowledge, and support to innovation, technological development, and decision support tools to minimize risk, avoid lasting harm, and optimize their contribution to the development of a sustainable ocean economy. Governments also require information and tools, for example, via national accounts that incorporate ocean indicators, to guide development of sustainable ocean economies and promote marine sectors.

Outcome 4: A predicted ocean where society understands and can respond to changing ocean conditions. The vast volume of the ocean is neither adequately mapped nor observed, nor is it fully understood. Exploration and understanding of key elements of the changing ocean including its physical, chemical, and biological components and Implementation Plan Version 2.0 interactions with the atmosphere and cryosphere are essential, particularly under a changing climate. Such knowledge is required from the land-sea interface along the world's coasts to the open ocean and from the surface to the deep ocean seabed. It needs to include past, current, and future ocean conditions. More relevant and integrated understanding and accurate prediction of ocean ecosystems and their responses and interactions will underpin the implementation of ocean management that is dynamic and adaptive to a changing environment and changing uses of the ocean.

Outcome 5: A safe ocean where life and livelihoods are protected from ocean-related hazards. Hydro-meteorological, geophysical, biological, and human-induced hazards create devastating, cascading, and unsustainable impacts for coastal communities, ocean users, ecosystems, and economies. The changing frequency and/or intensity of weather and climate- related hazards is exacerbating these risks. Mechanisms and processes for assessing priority risks, mitigating, forecasting, and warning of these hazards, and formulating adaptive responses are required to reduce short- and longer-term risks on land and at sea. Higher density ocean data and improved forecast systems—including those related to sea level, marine weather, and climate—are needed from near real time through decadal scales. When these enhancements are linked to education, outreach, and communication, they will empower policy and decision making, and they will mainstream individual and community resilience.

Outcome 6: An accessible ocean with open and equitable access to data, information, and technology and innovation. Inequalities in ocean science capacity and capabilities need to be eradicated through simultaneously improving access to and quality control of data, knowledge, and technology. This needs to be coupled with increased skills and opportunities to engage in data collection, knowledge generation, and technological development, particularly in Least Developed Countries (LDC), Small Island Developing States (SIDS), and Land-Locked Developed Countries (LLDC). Increased dissemination of quality controlled and relevant ocean knowledge to the scientific community, governments, educators, business and industry, and the public through relevant and accessible products will improve management, innovation, and decision making contributing to societal goals of sustainable development.

Outcome 7: An inspiring and engaging ocean where society understands and values the ocean in relation to human well-being and sustainable development. In order to incite behavior change and ensure the effectiveness of solutions developed under the Decade, there needs to be a step change in society's relationship with the ocean. This can be achieved through ocean literacy approaches, formal and informal educational and awareness raising tools, and through measures to ensure equitable physical access to the ocean. Together, these approaches will build a significantly broader understanding of the economic, social, and cultural values of the ocean by society and the plurality of roles that it plays to underpin health, well-being, and sustainable development. This outcome will highlight the ocean as a place of wonder and inspiration, thus also influencing the next generation of scientists, policy makers, government officials, managers, and innovators.

On each of the 2 days of the meeting, five concurrent sessions were organized around The Decade Challenges to identify overarching scientific questions, commonalities of approach, potential partnerships, as well as major gaps in understanding and technologies. In this issue of the *MTS Journal*, the Ocean-Shot authors are provided an opportunity to further share their ideas and, in doing so, open opportunities for new collaborations and partnerships with potential for engagement across many sectors of the ocean research community.

Building on the success of the Launch Meeting and the remarkable response to the call for Ocean-Shots, the USNC will foster further development of the Ocean-Shot concepts, now within the context of The UN Decade Implementation Plan's defined "Outcomes" (see box). Teams will be formed around the Outcomes, and Ocean-Shot authors will be brought together in virtual dialogs to identify synergies, aggregate ideas and approaches, and further expand or refine their concepts. The Committee will encourage engagement with other disciplines through the expertise available in other NASEM boards and divisions and through interaction with industry, to ensure that a broad, interdisciplinary approach can be applied to advance the science. U.S. funding agencies, the private sector, NGOs, and philanthropic organizations will be encouraged to join these dialogs to contribute to the maturation of these ideas into compelling program concepts and to explore potential partnerships and sponsorship opportunities. In concert with these activities, the USNC will continue coordinating activities, exchanging ideas with other national committees, and exploring opportunities to incorporate Ocean-Shots into broader international efforts.

The overwhelming response to the first call for Ocean-Shots is indicative of the skill, creativity, and enthusiasm of the U.S. marine science and engineering community, along with its deep concern for developing innovative and transformative research approaches that will lead to more sustainable management and stewardship of our ocean resources. It is, however, just the beginning. As described above, the USNC will work with the authors of the Ocean-Shots to evolve and mature the concepts, but at the same time, there will be additional calls for Ocean-Shots as well as opportunities to join in existing programs. We will also be actively recruiting the involvement of early career scientists and engineers to engage a diverse next generation(s) in defining and implementing the science and engineering that will lead to the ocean we need for the future we want.

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SMART Subsea Cables for Observing the Ocean and Earth

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ABSTRACT

The Joint Task Force (JTF) for Science Monitoring And Reliable Telecommunications (SMART) Subsea Cables will facilitate integration of sensors into commercial submarine telecommunications cables for climate monitoring and disaster warning. Our vision is a planetary scale array monitoring ocean heat and circulation and sea-level rise and revolutionizing real-time warning systems for earthquake and tsunami disaster mitigation. This is enabled by the trans-ocean cable infrastructure linking society together: 1.4 million km of cable, 20,000 repeaters every 70 km hosting the sensors, constantly being refreshed over 10–25 years, without interfering with telecom. Initial sensors are ocean bottom temperature, pressure and seismic acceleration. System suppliers are on board, the first major SMART project is funded and underway in Portugal (2020), and seven others are in various stages of planning and funding—a perfect example of the Blue Economy in action for the UN Decade.

JTF will provide coordination between ocean science, operational oceanography, hazard early warning centers, industry, and relevant government agencies. SMART cables will create profound opportunities for innovation—requiring people with appropriate depth and breadth of expertise. JTF will facilitate SMART cable projects that will catalyze and include education, training, and outreach programs to build necessary capacity

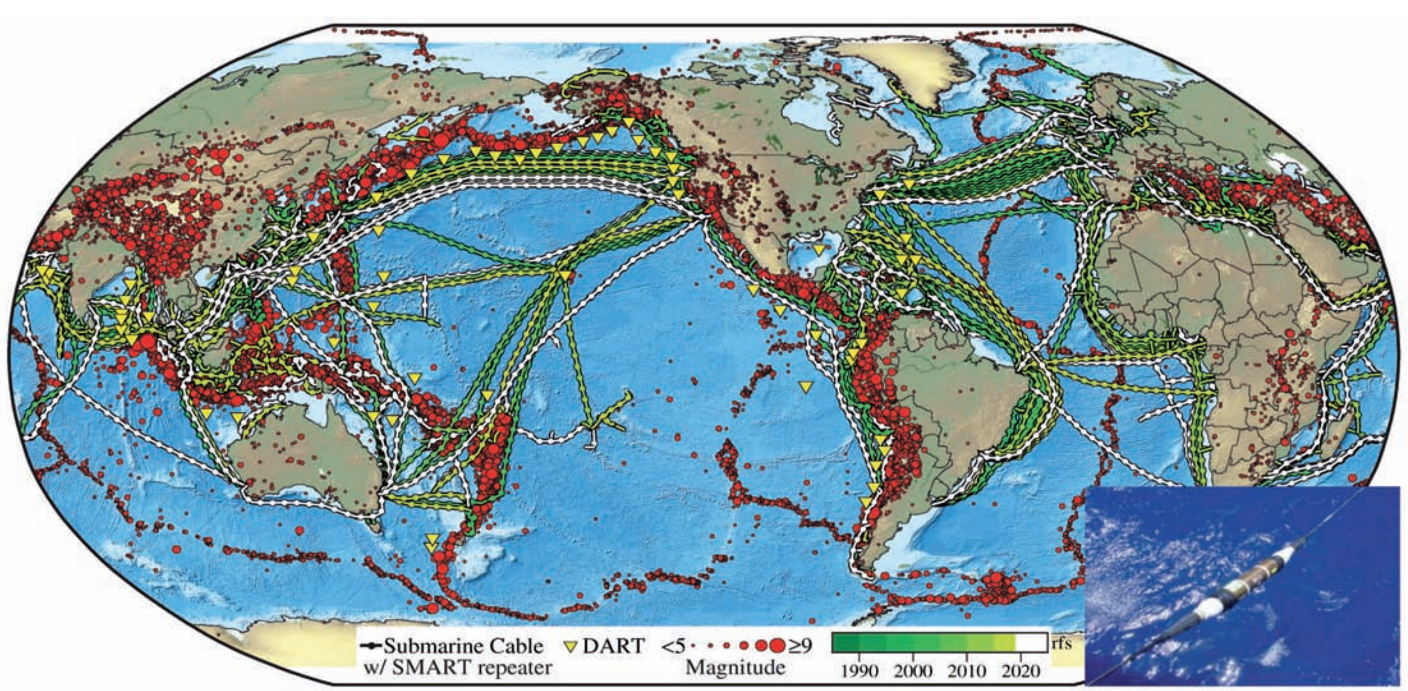

FIGURE 1. The global submarine telecommunication network as of early 2021, comprising 1+ million km of cable, refreshed and expanded on a 10–25 year time scale. Potential SMART repeaters are indicated as dots every 300 km. Color (green-white) indicates year ready for service. The inset shows a typical repeater (courtesy of Alcatel ASN). Red dots show historical earthquakes and magnitude. Yellow triangles are DART tsunami warning buoys. Joint Task Force SMART Subsea Cables: https://www.itu.int/en/ITU-T/climatechange/task-force-sc

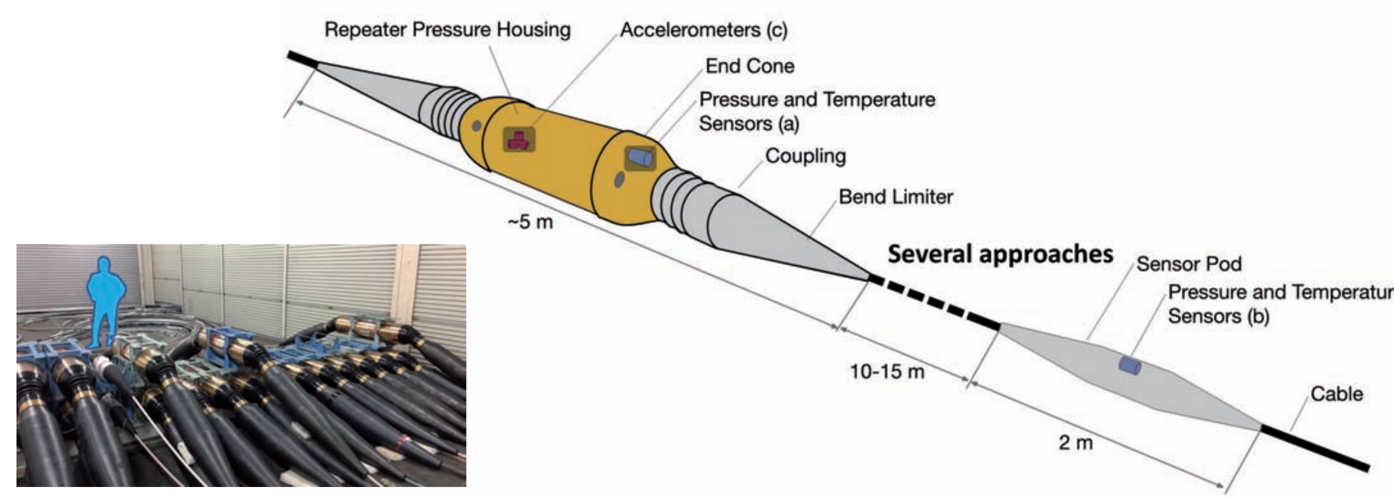

FIGURE 2. Two possible approaches to integrating sensors into SMART cables, either directly in/on a repeater housing and/or in a nearby sensor pod. The inset shows repeaters for a trans-ocean cable system.

Vision and Potential Transformative Impact

The mission of the UN ITU/WMO/IOC Joint Task Force (JTF) for **S**cience **M**onitoring **A**nd **R**eliable **T**elecommunications (SMART) Subsea Cables is to facilitate the integration of sensors into commercial submarine telecommunications cables for climate monitoring and disaster warning. Our vision is a planetary scale array of sensors monitoring ocean heat and circulation and sea level rise and revolutionizing real-time warning systems for earthquake and tsunami disaster mitigation to save lives. This transformative first-order addition to the ocean and Earth observing system is enabled by the trans-ocean submarine telecommunications cable network infrastructure linking society together: 1.4 million km of cable with 20,000 repeaters every 70 km hosting the sensors, constantly being refreshed on a 10–25 year cycle. Science, blue economy, and ocean safety will be significantly advanced without interfering with telecom. Initial sensors will be ocean bottom temperature, pressure, and seismic acceleration; this suite can be progressively expanded. The sensors will improve the cable network integrity, reliability, and resiliency. The first major SMART project is funded and underway in Portugal (2020); seven others are in various stages of planning and funding. Many of these initiatives provide uniquely economically viable solutions to multi-hazard monitoring in developing and smaller member states.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

SMART Cables are realizable, building on the last 25 years of submarine cable technical developments in telecom and science/early warning systems (e.g., NSF OOI, S-net, Ocean Networks Canada), as well as the continuing demand for Internet connectivity enabled by submarine cables. Alcatel Submarine Networks' (ASN) press release in September 2020 stated their recognition of the need to proactively address climate change and indicated they would supply integrated telecom+science/early warning systems. The next day, the Portuguese government announced the Continent, Azores, and Madeira Islands (CAM2) system, with seismic and environmental sensors (3,700 km, €120M, 2024+), demonstrating demand for the industry. Other suppliers are expected to follow suit, including SubCom in the U.S. and NEC in Japan.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

By entraining telecom, SMART Cables, the Ocean Science community, and the UN Decade can leverage all the resources of the industry — the Blue Economy, immense by "our" standards. To realize this, JTF will provide coordination between the industry, ocean science, operational oceanography (GOOS) and tsunami and other sea-level hazards early warning (IOC TOWS), and the relevant national government agencies and ministries. There are benefits for cable protection, detecting fishing, trawling and anchoring, as well as landslides and earthquakes, that can compromise cables. In Portugal, monitoring and managing the EEZ (e.g., illegal fishing) is part of the equation.

Opportunities for International Participation and Collaboration

The last decade of transformative SMART Cable planning and advocacy has led to the CAM2 system, a Wet Demo off Sicily (INGV, underway, €2.4M/EC+Italy, 2022), and other emerging systems in various stages including: Vanuatu-New Caledonia (planning, €2.5M/France on table); Indonesia (pilot systems under development); MEDUSA (Western Med; commercial/EU funding, RFP to include SMART capability); French Polynesia (RFP in process); Namaste (India-Oman, planning, commercial); New Zealand-Chatham Islands (discussion); and Nzadi (Angola, planning, commercial). All of the planning includes local science and early warning colleagues, owners/funders, government, and suppliers; it is inherently an international process.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers and Technologists

The fundamental technical innovation of SMART Cables is the provision of a power (*sine qua non* for everything else) and communication interface on the seafloor from shallow to deep with global distribution, enabling real-time interdisciplinary observations. This will create profound opportunities for innovation—requiring people with appropriate depth and breadth of expertise. The JTF will facilitate SMART Cable projects that will catalyze and include education, training, and outreach programs to build necessary capacity and interest, including youth and early career professionals, in ocean data. Special efforts will also be made to engage local communities and utilize traditional knowledge.

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Ecological Forecasts for a Rapidly Changing Coastal Ocean

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ABSTRACT
The U.S. Integrated Ocean Observing System (IOOS) has a vision to provide ecological forecasts that inform response to multiple stressors in the face of rapid changes in our ocean and Great Lakes. IOOS supports 11 nationally distributed Regional Associations, eachwith established ties to local decision makers and regional coastal scientists. IOOS also supports thematic networks of platforms and observations to characterize and monitor marine ecosystems and living resources throughout the nation. IOOS serves as the U.S. contribution to the Global Ocean Observing System. This infrastructure, stakeholder engagement, and local-to-global reach uniquely positions IOOS to advance development of an ecological forecast system, across sectors and disciplines, that is responsive and effective.

Vision and Potential Transformative Impact

The health of our coastal communities, economies, and ecosystems depends upon not only on understanding the complexities of changing coastal conditions but also the ability to provide timely high-resolution forecasts for decision making. With increasing rates of environmental change, the need for more comprehensive information on our coasts has never been greater. Additionally, since climate and weather drivers play out differently in diverse ecosystems, depending on habitat, species, and societal dependencies, the distributed approach and regional connections that IOOS offers is a large advantage.

The vision is to provide accessible and informative forecasts for a variety of users on how changes—from genes to cells to organisms to the ecosystem—may impact their lives, livelihoods and property. With a click of a computer mouse or mobile device, fishermen, shellfish farmers, emergency managers, resource managers, and others will access forecasts of future conditions that show all aspects of the ecosystem in four dimensions: latitude, longitude, depth, and time. Interactive tools will allow users to quickly test scenarios and hypotheses to determine the best course of action.

Success will depend on an interdisciplinary approach at multiple scales with robust observations to support, validate, and advance our predictive capacity. Social scientists, modelers, oceanographers, computer scientists, product developers, and communication experts will work together and with users to develop end-to-end capabilities. Advances in remote and autonomous sensing, machine learning, and the Internet of Things makes this possible. Such a system will transform our ability to respond and adapt to ecosystem changes at local, regional, national and global scales.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The U.S. Integrated Ocean Observing System (IOOS), with its partnership of 17 federal agencies, national network of 11 Regional Associations, and numerous private sector partners, provides the foundational infrastructure for robust ecological forecasting. IOOS provides services to the entire coastline of the United States and links federal expertise with regional scientists, management agencies, the private sector, and non-governmental agencies. IOOS partners include the Marine Biodiversity Observation Network (MBON), the Animal Telemetry Network (ATN), the Ocean Acidification Program, among others. Two grant programs administered by IOOS, the Ocean Technology Transfer program that supports the transition of emerging technology to operations and the Coastal Ocean Modeling Testbed that serves as a conduit between federal operations and the research community, along other federal and private sector investments, will spur the needed innovation.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Scientific and technical innovations will allow for assimilation of high temporal and spatial resolution observations into multiple stressors, operational, multi-scale forecasts. Social scientists, economists, and IT experts will develop models and forecasts, while graphic artists, professional communicators, and product design experts will deliver state-of-the-art visualizations that are tailored to the needs of the users. Success will depend on a diverse partnership and an interdisciplinary, iterative approach focused on meeting user needs.

FIGURE 1. U.S. IOOS provides ocean observing and ecological forecasting infrastructure and capability in 11 regions throughout the United States and territories,from the head of tide to the EEZ.

Indigenous communities, citizens, local communities, fishermen, aquaculturists, energy companies, maritime industry, and others will be part of the process to ensure effective and efficient information for decisions and actions.

Opportunities for International Participation and Collaboration

The North Atlantic Current, Labrador Current, Gulf Stream, California Current System, and other major currents drive climate, weather, and ecosystems well beyond U.S. jurisdiction. IOOS is the U.S. regional contribution to the Global Ocean Observing System (GOOS), and collaborates with many international partners. IOOS will build on existing close ties with neighbors in the Atlantic Basin, Gulf of Mexico, Great Lakes, Arctic, Caribbean, and throughout the Pacific to reach other global partners. Collaboration will enhance the sharing of information, knowledge, and best practices, development of standards for integration, and test new tools and techniques.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Novel approaches to ecological forecasting and information delivery will depend on fresh ideas and a willingness to work across disciplines. Graduate fellowships, graduate student support, design competitions, hack-a-thons, and other techniques will encourage and support young scientists. The IOOS network provides a unique opportunity to test ideas in multiple environments and broaden young scientists' understanding and exposure. International mentorships can serve young professionals from around the world. IOOS would seek to coordinate with existing platforms such as the IOC Ocean Teacher Global Academy for broadest reach of training, testbeds, and materials.

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Measuring Global-Mean Sea-Level Rise With Surface Drifting Buoys

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ABSTRACT

We propose to establish a new ocean observing system for monitoring global and regional mean sea-level changes. This system will consist of a global array of thousands of water-following drifting buoys tracked by a global navigation satellite system—such as the Global Positioning System (GPS)—which will continuously provide the geographical positions and the height of the sea surface along the buoys' trajectories. The sea-level height data collected in this way, averaged over regional basins and the global ocean, will provide daily measures of regional and global mean sea levels. An essential climate variable, mean sea level is an intrinsic measure of climate change, integrating the thermal expansion of the ocean's waters and additions to the ocean's mass from melting terrestrial ice. The realization of this new system requires that standardized vertical position measurements with controlled accuracy be acquired and regularly transmitted from relatively small and expendable drifting buoys, which constitutes a technological challenge, yet one with a clear path for being met. The development and implementation of this ocean shot concept will ultimately provide an independent, resilient, sustainable, and economical observational system to quantify natural and anthropogenic sea-level changes, augmenting the existing satellites and tide gauge observing systems.

Vision and Potential Transformative Impact

Currently, global-mean and regional sea-level changes are monitored by two observational systems: coastal and island tidal gauges and satellite radar altimeters. Tidal gauge records have high temporal resolution, but their representativeness of the global-mean sea level is biased toward the coasts and the Northern Hemisphere. In contrast, the altimeter reference record is almost global but can only provide a near-synoptic view about every 10 days and spatial resolution of hundreds of kilometers. The envisaged observing system will be high frequency, such as daily, and it will be global by notably including the highest latitudes such as in the Arctic ocean. The new system will be independent of the other systems, but also resilient and scalable, fit-for-purpose and economical, rapidly deployable and adaptable to new technologies and scientific objectives related to understanding and adapting to the threat of the sea-level rise and climate change. Importantly, the new system will introduce an important redundancy that would preserve the continuity of the record in case of failure of key satellite missions.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

A global network of drifting buoys already exists in the form of the Global Drifter Program (GDP), the principal component of the international Data Buoy Cooperation Panel. The GDP is sustained by U.S. federal agencies, with engagements from other countries.

The proposed observing system could be quickly deployed by enhancing the positioning technology of GDP drifters, adding to its scientific value and expanding its existing objectives by adding the capability to measure mean sea level. The GDP buoys already use GPS technology to measure surface currents together with sea surface temperature, atmospheric pressure and, and for some, salinity, providing an oceanographic context to new sea-level measurements. Importantly, the GDP readily provides the framework for technological development by Scripps Institution of Oceanography and other commercial companies already building drifters, and the logistical infrastructure for deployment and data processing by the NOAA Atlantic Oceanographic and Meteorological Laboratory.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

A recent study (Elipot, 2020), demonstrate that, with the current characteristics of the existing GDP array of 1,250 drifters, global-mean sea-level decadal linear trend estimates with an uncertainty less than the recommended 0.3 mm per year could be achieved with daily random error of 1.6 m or less in the vertical direction for each individual drifter daily estimate. With a pilot project currently underway, this technological challenge will be overcome by combining research and development in global navigation satellite system science, signal processing, and geodesy.

FIGURE 1. Shane Elipot deploying a drifter from the NOAA Ship Ronald H. Brown. Photo Credit: Molly Baringer, NOAA.

Opportunities for International Participation and Collaboration

The accuracy of measuring global-mean sea-level change from an array of drifting buoys improves not only with the individual vertical accuracy of a drifter height measurement, but also with the number of active drifters (Elipot, 2020). Just like the current GDP relies on international collaborations for buoy deployments in the world's ocean, the proposed array will also need international participation for its implementation and funding. As such, the ultimate scale of the proposed observing system constitutes a clear example of the application of slogan "the science we need for the ocean we want."

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Globally distributed deployments of buoys by international partners, and the associated stream of oceanographic data, provide opportunities for individual, institutional, and community engagements. As an example, sea level and other data from a single buoy could relatively easily be apprehended by a single investigator or student. Such individual engagement could ignite further investigations, which would include a large number of drifters requiring wider coordination and expertise through a multi-people project, building into the global capacity of the proposed system.

FIGURE 2. A drifter of the NOAA Global Drifter Program near Tristan da Cunha Island.

Reference

Elipot, S. 2020. Measuring global mean sea level changes with surface drifting buoys. Geophysical Research Letters, 47, e2020GL091078. https://doi.org/10.1029/2020GL091078.

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Envisioning an Interconnected Ocean: Understanding the Links Between Geological Ocean Structure and Coastal Communities in the Pacific

Megan Lubetkin and **Nicole Raineault**, Ocean Exploration Trust; **Sarah Gaines**, University of Rhode Island, Coastal Resources Center

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ABSTRACT

Covering nearly one third of the Earth's surface, the Pacific Ocean contains many significant interconnected geologic features extending into the coastal zone and the islands themselves. Trenches, ridges, seamount chains, faults, and fracture zones are not only fundamental expressions of Earth processes but also fundamental to life. Without awareness of these features and their natural and cultural importance, marine management and global understanding will remain disjointed. The Ocean Exploration Trust (OET) will spend the next several years in the Pacific conducting scientific expeditions to better understand the ocean through seafloor mapping and ocean exploration. Western ocean science is one of many ways to perceive and value the structural features of the Pacific. Communities across Pacific islands—often volcanic peaks emerging from deep below—are interconnected by water and by the underlying seafloor. We acknowledge the knowledge from local communities and recognize the multitude of ways to conceptualize and relate to the Pacific. With the University of Rhode Island's Coastal Resources Center (CRC), OET seeks to collaborate with local communities to reveal the structural significance and interconnected nature of oceanic features, making a link to the livelihoods of Pacific islanders. Further objectives would be co-designed with partners from local communities.

Vision and Potential Transformative Impact

Envisioning an interconnected ocean. To re-envision the Pacific Ocean as an interconnected space rather than an isolated one, this project will link scientific knowledge and exploration of structural marine features to local communities' traditional wisdom and understanding of the interrelation of Pacific islands and other oceanic features.

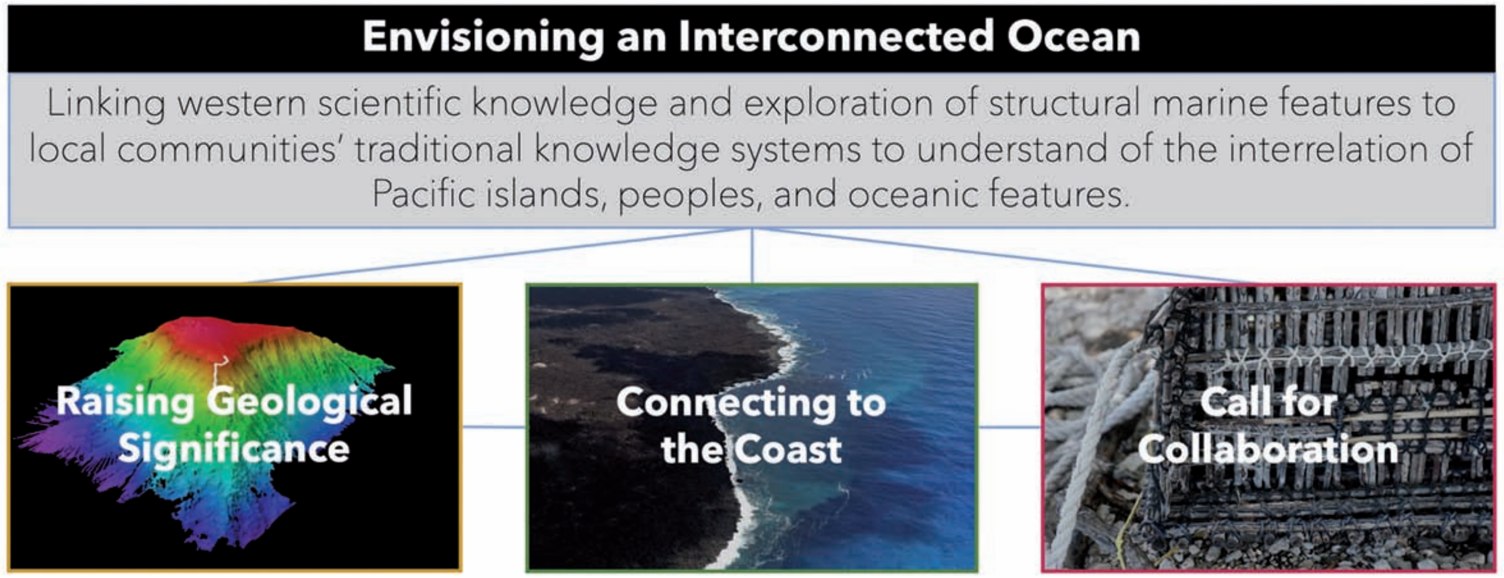
Raising geological significance. Through two-way engagement around the connections the seafloor provides across the Pacific and the geoheritage of this seafloor, this initiative will: bridge underrepresented perspectives to share the significance of geological features and explore new ways of communicating and educating, and seek recognition at the level with biodiversity values, which are increasingly recognized across marine protected areas and the high seas.

Connecting to the coast. By illuminating the continuity between deep-sea geology and coastal communities, the project hopes to unearth new understandings of the values of this resource for different stakeholders, linking exploration research with coastal livelihoods. We plan to illustrate and visualize the ocean, including the seafloor, as a network of interrelated features that are known and celebrated as a complex whole, connecting to management approaches such as marine spatial planning, marine protected areas and Blue Economy efforts to identify and quantify the value of marine resources.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

With only ~20% of the global ocean mapped, tens of thousands of geologic features remain unresolved and unexplored. OET, a co-partner in the National Oceanic and Atmospheric Association's Ocean Exploration Cooperative Institute (OECI) since 2019, along with several academic institutions, continues to map, explore, educate, and spread a new understanding of the Pacific. Through the URI Graduate School of Oceanography's Inner Space Center, the exploration is shared live to the public globally with additional support for one-to-one and one-to-many live broadcasts.

The CRC helps communities become more effective stewards of their coastal and marine resources locally in Rhode Island and around the world. CRC partners with stakeholders to apply science and find solutions to societal issues. Working with communities, other universities, industry, and government, we respond to issues that matter and to build capacity. Expertise at CRC includes a member of the U.S. Advisory Group on Geoheritage and Geoparks.



Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

We will pursue collaborations with artists, storytellers, craftspeople, and educators globally to illustrate the structural significance of the Pacific. OET and CRC have extensive experience working at sea and along coasts with communities, across disciplines outside of traditional ocean sciences. We will co-design and co-produce works that bring together different perspectives for a shared purpose. OET is currently developing a new physical venue and virtual space (opening 2024/5) for encountering the deep-sea through transdisciplinary exhibitions and events. The knowledge gathered and the works produced from this project could be exhibited in this future oceanic venue and digital space.

Opportunities for International Participation and Collaboration

OET expeditions and outreach are conducted with the participation of researchers, students, educators, and the public worldwide. Although at-sea capacity of the ship is limited, an extended network of researchers are invited to participate in expeditions via telepresence where the live seafloor video and data are publicly broadcasted for global engagement. CRC has previously worked on coastal and fisheries management in the Pacific and has just won a USAID project on Pacific coastal fisheries management, engaging with local partners and international NGOs. Centered on the Pacific Ocean, an internationally significant space, we will seek international participation and community collaboration.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

OET will apply their robust education and outreach program that includes online educational STEM resources, an at-sea internship program for college students, and a Science Communication Fellowship. We conduct live outreach events including Q&A interactions with classrooms globally to allow the public to learn more about the expedition, the explorers, and pathways to pursue related careers. Through this concept we will continue to encourage and inspire the next generation of ocean scientists while broadening the scope of ocean sciences and ocean knowledge. The project will respond to the increasing demand of ocean science students for societally relevant research.

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COVERAGE: Next Generation Data Service Infrastructure for a Digitally Integrated Ocean Observing System in Support of Marine Science and Ecosystem-Based Management

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ABSTRACT

Ocean science and decision support applications increasingly rely on the synergistic, interdisciplinary use of multivariate data from distributed agency repositories. While more available, the growing variety and volume of ocean observing data combined with the heterogeneous modalities of access continue to pose a challenge to broadscale uptake. This limits the effective utilization of costly investments in sustained ocean observation by an increasing diversity of user communities with a need for such environmental information on the oceans for the assessment of climate change and other ecosystem impacts. Leveraging an advanced cloud technology stack and an ongoing multi-agency pilot effort being spearheaded by NASA, the CEOS Ocean Variables Enabling Research and Applications for GEO (COVERAGE) initiative seeks to collaboratively develop the next generation data service infrastructure for a more digitally integrated ocean observing system in support of marine science and ecosystem-based management. In particular, we envisage the implementation of a data services layer atop of existing agency repositories to provide more harmonized access to satellite, in-situ, and model data across a fragmented ocean data landscape with a set of value-added services that include integrated data search, visualization, and analytics. Here we outline the motivation and importance of this effort plus efforts thus far towards the collective realization of this ambitious vision.

Vision and Potential Transformative Impact

There is a growing imperative to better marshal available ocean observations of different types in support of marine science and resource management applications for societal benefit. There is also a related need to develop improved data infrastructures and services for a more digitally integrated ocean observing system, one providing more seamless access to diverse observations for the oceans, remotely sensed and in-situ, that are proliferating rapidly in extent and type, to enable their synergistic and efficient use. This is also essential to more fully realize the potential of Earth observations both amongst emerging data user communities and a nascent value-added service sector that will be integral to the data-driven Blue Economy of the near future. This is a grand challenge and core vision motivating NASA's COVERAGE initiative.

The CEOS Ocean Variables Enabling Research and Applications for GEO (COVERAGE) initiative aims to address this critical gap. It seeks to provide improved access to multi-agency, multidisciplinary remote sensing data for the oceans that are also better integrated with in-situ observations, including biological, that pose additional data interoperability challenges. It focuses on implementing technologies, including emerging cloud-based solutions, to provide an advanced yet accessible data rich, web-based platform for integrated ocean data delivery and access: multi-parameter observations, easily discoverable and usable, organized thematically, available in near-real time, and complemented by a set of value-added data services. COVERAGE development is characterized by a phased, user-driven, open source approach organized around priority application use cases identified by agency partners, including GEO-MBON, and GEO-Blue Planet.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

COVERAGE is more than a concept. It is a formal initiative within the Committee on Earth Observation Satellites (CEOS) involving the United States (NASA, NOAA/NESDIS) and international participation, and an ongoing NASA R&D project currently entering its third year of implementation. Having successfully completed project scoping and prototype development phases (A and B), future Phase-C development focuses on hardening and further enhancement of COVERAGE technical capabilities and testing those under an expanded range of ecosystem application use cases. COVERAGE's involvement in the UN Ocean Decade as a CEOS cumulative contribution to SDG14 is seen as a step towards broader collaborative development of a next-generation data service infrastructure for ocean observation. Connection to regional observing systems and agencies involved in marine living resource assessment/management nationally as a complement to our current international agency partners in this space is realizable and an important goal. Given the important informatics technology focus of COVERAGE and our emphasis on FAIR data and open source software principles, there are also excellent opportunities for collaborations with federal agency, academia, and industry on ocean interoperability standards and data service infrastructure development. COVERAGE is a contributor to the ESIP Federation, NASA-ESDSWG, and other ocean data-related communities of practice.

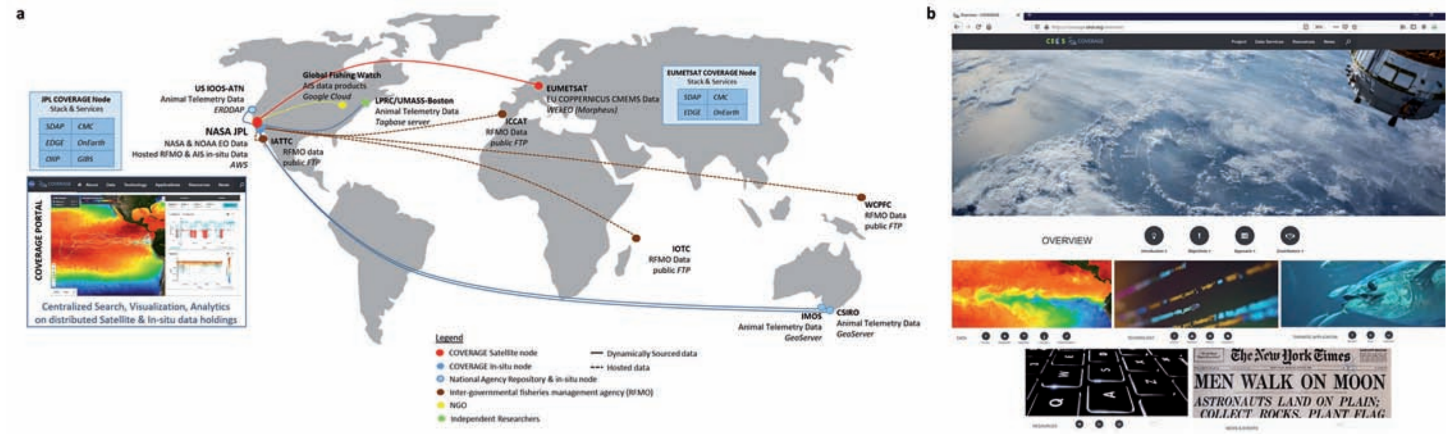

FIGURE 1. a) Distributed data architecture of the prototype COVERAGE system focusing on a pilot global pelagic ecosystem application. b) COVERAGE web portal (https://coverage.ceos.org).

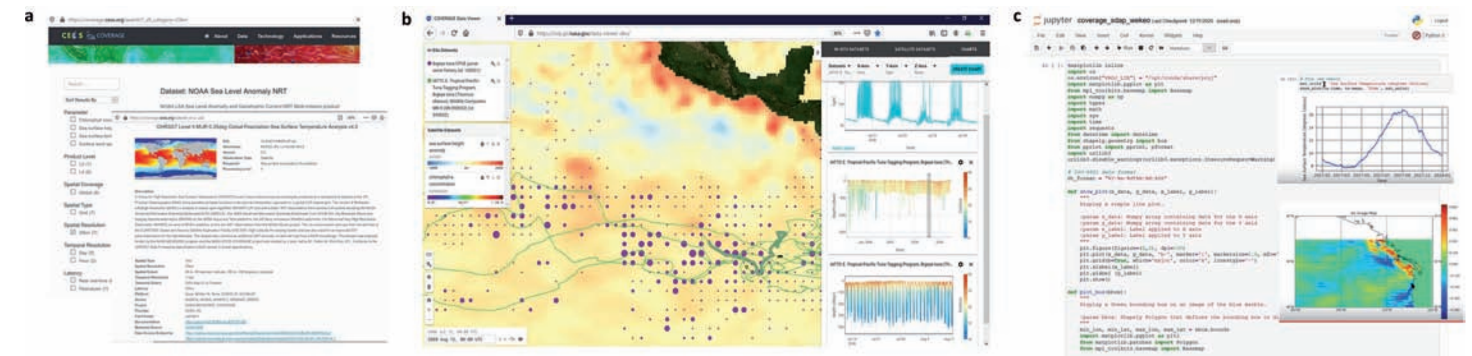

FIGURE 2. COVERAGE Phase-B project prototype web-based data services. a) Dataset search across agency metadata collections. b) Dynamic, integrated visualization of multivariate satellite and in-situ biophysical oceanographic data. c) COVERAGE cloud-based analytics services accessible via a Jupyter notebooks interface.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

With its emphasis on more integrated ocean data access across agency repositories and the leveraging of information technology innovation for the enablement of interdisciplinary ocean science and applications, COVERAGE is both cross-cutting and novel in its approach that is also strongly stakeholder focused and end-user driven. Illustration of the technology development is in the context of a pilot thematic application use cases involving the integration of multivariate oceanographic data in support of emerging ecosystem-based assessment and cross-sectoral marine spatial planning applications. Contribution towards the implementation of an improved ocean data service architecture atop of existing agency and institutional data repositories will not only the enable broader impact of ocean observation investments. This is also seen as critical for catalyzing the development of a value-added data service sector that has the potential to play an important role for the emergence of a data-driven Blue Economy.

Opportunities for International Participation and Collaboration

COVERAGE involves international participation and collaboration within the CEOS context. COVERAGE also enjoys the support of an external advisory board comprising experts representing multiple international agencies and initiatives. This includes IMOS, CSIRO, ABOM, GEO-MBON, and the Sargasso Sea Commission in addition to U.S. agencies (NASA, NOAA). COVERAGE is developing collaborations with the intergovernmental tuna RFMOs (IATTC in particular). COVERAGE is also engaged with the recently approved by GOOS animal telemetry ocean observation network (AniBOS) and the GEO-Blue Planet initiative. Planned interfacing with IOC-OBIS should provide additional international collaborative opportunities in future.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

COVERAGE is developing a generalized data infrastructure that will enhance global ocean observing informatics capacity. Simplified access through a set of value-added services will improve the impact of costly observations, promoting better utilization by a larger community of users, including non-experts. Browser-based access to data and computing resources will help reduce the current divide between those with resources and constrained communities, thus promoting core Open Science and FAIR principles. While COVERAGE currently does not include a capacity-building component beyond tutorials we provide, this is ripe for development in key areas such as ocean data and informatics technology literacy.

Acknowledgment: The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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Integrated Observing Across the Northwest Atlantic

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ABSTRACT

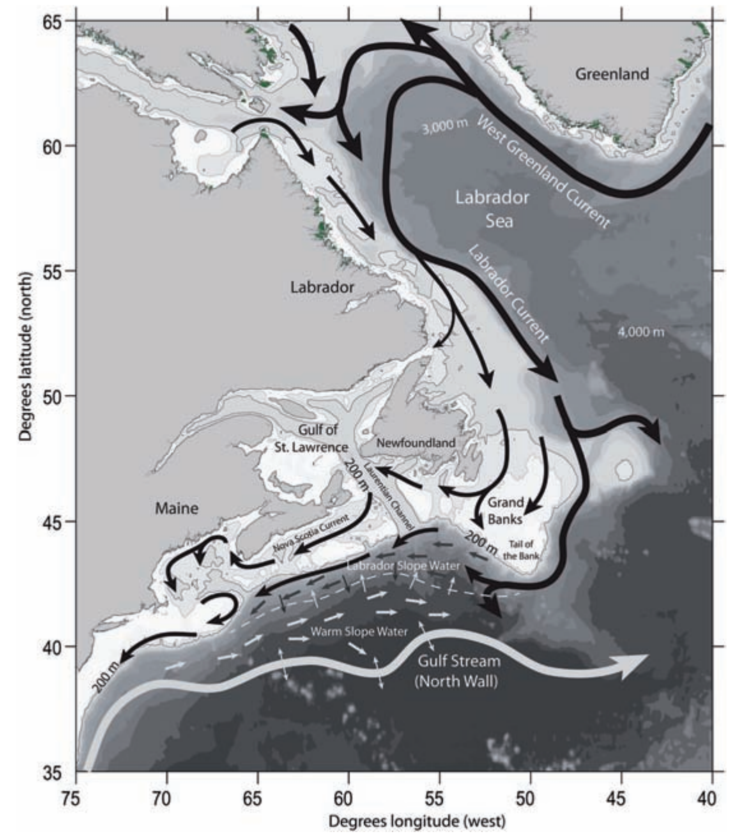
Northwest Atlantic current systems originating off Greenland extend south to the Canadian Maritimes and Northeastern United States, creating oceanographic, ecological, and economic connections that compel integrated ocean observing across the region. For more than a decade, NERACOOS has led development of a robust and responsive ocean observing system for the Northeastern U.S. as part of the U.S. Integrated Ocean Observing System (IOOS) and Marine Biodiversity Observation Network (MBON), components of the Global Ocean Observing System (GOOS). That experience, backed by key partnerships that reach into northern latitudes, positions us to build new partnerships toward integration of ocean observing at scale in the Northwest Atlantic. Strategic deployment of observing tools should be tailored to local conditions, with oceanographic models, satellite remote sensing, and data products unifying the system at scale. Indigenous people must be core partners, both as contributors of traditional knowledge and priority communities for capacity development. The diversity and complexity of human, environmental, and data systems calls for application of artificial intelligence and machine learning tools to extract key insights from disparate information sources. Longevity will be promoted by involvement of the private sector to build buy-in, and training of young practitioners to sustain the system into the future.

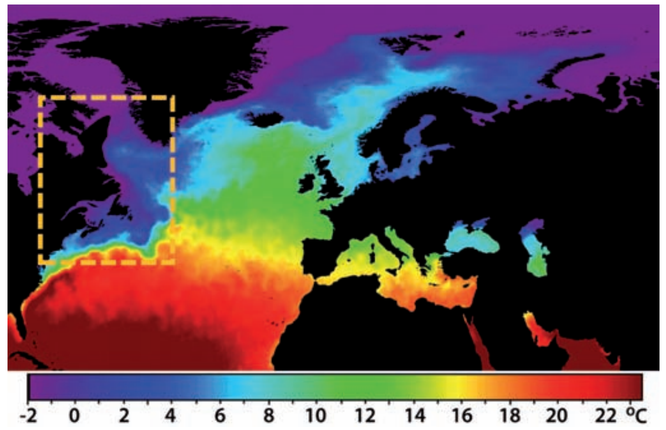
Vision and Potential Transformative Impact

We envision an interconnected system to track oceanographic and ecological changes from the Arctic to the Gulf of Maine integrating state-of-the-art technologies, Indigenous knowledge, and citizen science to better understand the rapidly changing Northwest Atlantic. The oceanographic influence of climate-driven changes in the Arctic extends well into mid-latitudes along the Northwest Atlantic coast. The Greenland Current feeds the Labrador Current, which carries waters of Arctic origin over the Scotian Shelf into the Gulf of Maine. Distributions of many species are shifting northward against this flow, bringing new species into contact with ocean-dependent communities as others are lost. Amidst these changes, ocean observing systems are inconsistent and uncoordinated. By convening agencies, institutions, Indigenous communities, and private sector stakeholders from the United States, Canada, and Greenland, we can build systems to track and communicate changes with greater speed and at scale. This region is especially important for global understanding of and responses to climate change given that the Northwest Atlantic is the largest carbon sink in the world. Local portfolios of observing assets will vary across this domain due to differences in geography, population density, ocean uses, and other factors, but satellite remote sensing, oceanographic models, and data products paired with international communities of practice, knowledge sharing networks, and capacity building initiatives can unify observing at scale. This can be a model for multinational partnerships across other major current systems grappling with environmental change.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

For more than a decade, NERACOOS has implemented U.S. IOOS and MBON in the Northeastern United States, in collaboration with NOAA and a range of other scientific, government, and industry partners. U.S. IOOS has made significant strides toward advancing GOOS, with valuable lessons for neighbors in the Northwest Atlantic and systems that can be expanded to encompass the larger region. In return, cooperation with these neighbors can improve understanding of both episodic oceanographic events and persistent changes originating in upstream areas. NERACOOS employs a diverse portfolio of technological tools—fixed moorings, autonomous gliders, high-frequency radar, satellite remote sensing, ships of opportunity (SOOPs), and more—including cost-sharing and operational arrangements with a variety of governmental and private sector partners. The Northeast Coastal Ocean Forecast System maintained by NERACOOS and the University of Massachusetts extends to Arctic waters, presenting an operational framework through which to investigate large-scale process and shape coordinated observing systems. The NOAA Northeast Fisheries Science Center has recently resumed U.S. support for the trans-Atlantic Continuous Plankton Recorder (CPR) program, which relies on commercial SOOPs traversing international routes. NERACOOS is planning to manage CPR data from U.S. waters, presenting a model public–private partnership from which to build.





Current systems in the Northwest Atlantic create strong oceanographic connections from the waters off Greenland around the Canadian Maritimes to the Northeastern United States (left). This connectivity causes Arctic influence to extend further south into mid-latitudes in the region than anywhere else in the Atlantic Basin (above). (Left: Townsend et al., 2015; Above: U.K. National Oceanography Centre)

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Indigenous cultures across this region, including the Inuit in Greenland, Mi'kmaq in Canada, and the Wabanaki tribes of the United States, should be key members of this initiative. Ocean observing systems should evolve to meet the unique needs of these communities, which harbor traditional knowledge that can in turn be an invaluable contribution to those systems. Diverse maritime industries—seafood, shipping, energy, tourism, and more—present additional sources of data, as well as platforms for deploying sensors and collecting data. The rising need for comprehensive accounting of marine carbon stores is an opportunity to advance new science that integrates the breadth of knowledge and data systems. This need is stronger than ever for the world's largest carbon sink in the Northwest Atlantic in light of changing climate policy priorities in the United States. To understand carbon budgets and other complex dynamics using disparate types of information, artificial intelligence and machine learning need to become central elements of ocean observing. As these tools advance understanding, innovations in materials science can promote development of new sensors. This initiative presents an ideal opportunity to develop and test new tools across geographic, oceanographic, ecological, and socio-cultural gradients.

Opportunities for International Participation and Collaboration

NERACOOS is joined by several international partners in developing this initiative. CIOOS Atlantic coordinates observing in the waters of Atlantic Canada. Asiaq Greenland Survey conducts oceanographic observing and analysis further north. The Ocean Tracking Network (OTN) studies movements, habitats, and survival of aquatic animals across international boundaries. The Ocean Observatories Initiative (OOI) is an integrated program measuring ocean processes across the Atlantic basin. Innovasea designs advanced solutions for fish tracking and farming worldwide. These partners provide a foundation of key national organizations (Asiaq, CIOOS Atlantic, NERACOOS), international scientific initiatives (OTN, OOI), and the private sector (Innovasea) from which to build.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Universities in each of the four countries will also be core partners to facilitate education and involvement of younger practitioners, including support for graduate student projects, mentorship of young practitioners, opportunities for service on oversight and advisory bodies, and other activities. A particular focus on engaging with young Indigenous people will seek to counter centuries of marginalization and disempowerment through visibility, capacity building, and provision of services needed by these communities.

Reference

Townsend, D.W., Pettigrew, N.R., Thomas, M.A., Neary, M.G., McGillicuddy Jr., D.J., & O'Donnell, J. 2015. Water masses and nutrient sources to the Gulf of Maine. Journal of Marine Research, 73(3-4):93-122. https://doi.org/10.1357/00222401581584881

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METEOR: A Mobile (Portable) ocEan roboTic ObsErvatORy

Kanna Rajan, SIFT LLC and University of Porto; **Fernando Aguado**, University of Vigo; **Pierre Lermusiaux**, MIT; **João Borges de Sousa**, University of Porto; **Ajit Subramaniam**, LDEO/Columbia University; **Joaquin Tintore**, SOCIB and IMEDEA (CSIC-UIB)

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ABSTRACT

The oceans make this planet habitable and provide a variety of essential ecosystem services ranging from climate regulation through control of greenhouse gases to provisioning about 17% of protein consumed by humans. The oceans are changing as a consequence of human activity but this system is severely under sampled. Traditional methods of studying the oceans, sailing in straight lines, extrapolating a few point measurements have not changed much in 200 years. Despite the tremendous advances in sampling technologies, we often use our autonomous assets the same way. We propose to use the advances in multiplatform, multidisciplinary, and integrated ocean observation, artificial intelligence, marine robotics, new high-resolution coastal ocean data assimilation techniques and computer models to observe and predict the oceans "intelligently"—by deploying self-propelled autonomous sensors and Smallsats guided by data assimilating models to provide observations to reduce model uncertainty in the coastal ocean. This system will be portable and capable of being deployed rapidly in any ocean.

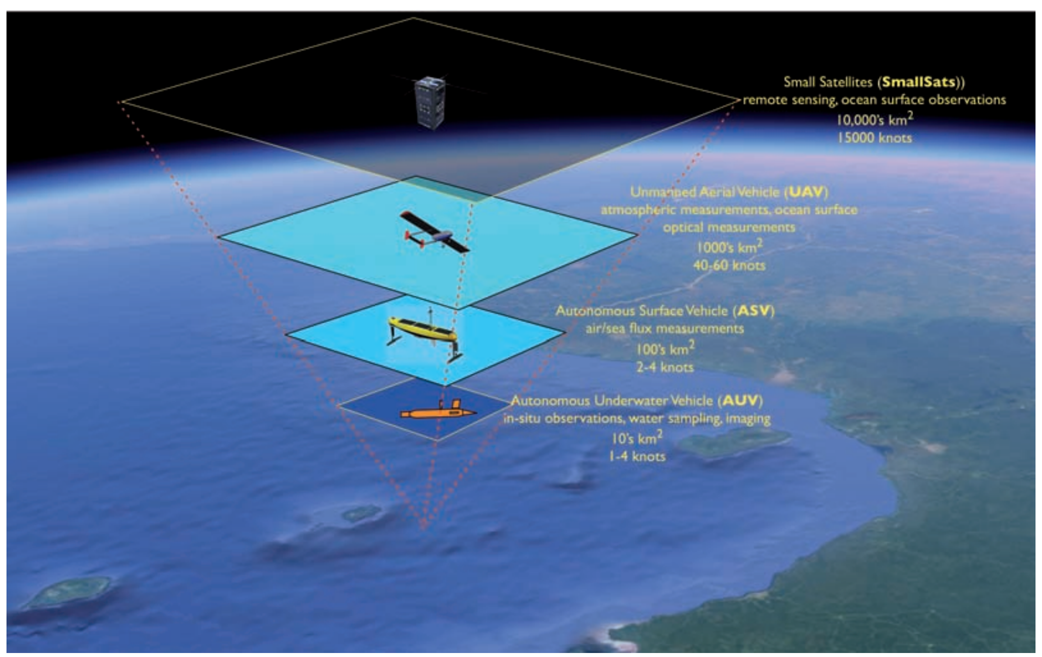

FIGURE 1. METEOR is focused on coastal ocean observation and brings together advances in technology by integrating command and control software that uses Artificial Intelligence (AI) to drive ocean data gathering by networked autonomous platforms, small satellites with data assimilating models, complemented by more traditional shipboard sampling. The end result will be a mobile, portable coastal ocean observatory that can provide information to stakeholders and communities.

Vision and Potential Transformative Impact

Our vision for METEOR (A Mobile [portable] ocEan roboTic ObsErvatORy) is about a paradigm change in coastal ocean observation and response with the development of actionable knowledge about the ocean. We propose to advance ocean observation modalities by integrating command and control software that uses artificial intelligence to drive ocean data gathering by autonomous platforms, small satellites with data assimilating models, complemented by more traditional shipboard sampling. The self-propelled robotic platforms will be directed to regions of the model field with maximum uncertainty to provide data that can be assimilated into the model to reduce that uncertainty.

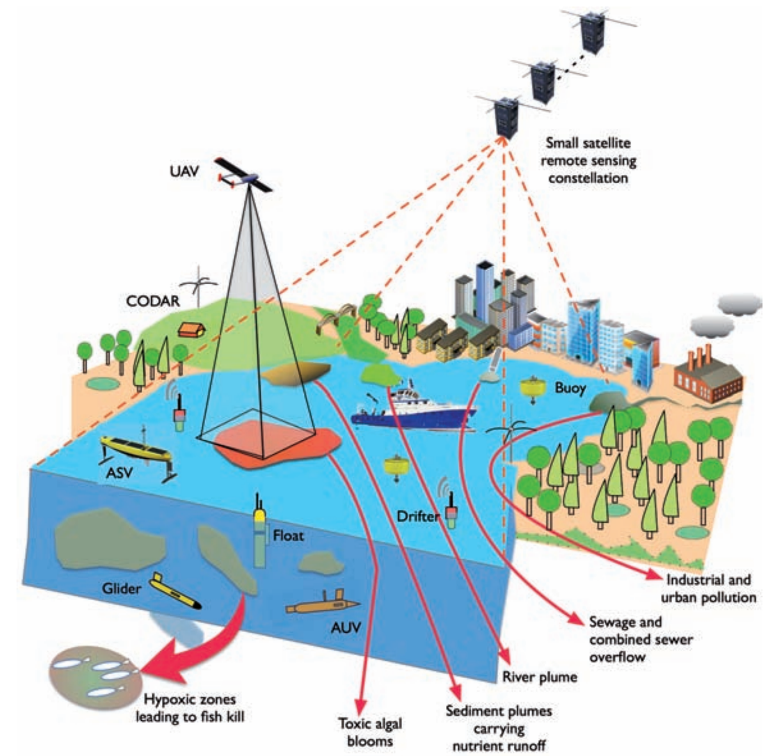

FIGURE 2. In METEOR, self-propelled robotic platforms will be directed to regions of the model field with maximum uncertainty to provide data that can be assimilated into the model to reduce that uncertainty. The platforms will use the model output of flow fields to efficiently relocate to other regions of the model grid to further reduce mode uncertainty. "Intelligent" deployment of in-situ assets in this manner will help produce higher-resolution model output while reducing the time and energy needed for ocean observation. While METEOR will use a substantial amount of robotic hardware, the focus is on the software capabilities, which will provide high-value information coupled with high-revisit times (~ 3–5 hours) of satellite remote sensing products to close the sense-assimilate-predict-sample loop.

The platforms will use the model output of flow fields to efficiently relocate to other regions of the model grid to further reduce uncertainty in the model. "Intelligent" deployment of in-situ assets in this manner will help produce better model output while reducing the time and energy needed for ocean observation. METEOR will be a modular system with bespoke approaches to ocean observation. It will integrate state-of-the-art hardware including a small satellite (SmallSat) constellation, in-situ air, surface and underwater vehicles with software to control and visualize the information gathered.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The PI of METEOR is from private industry specializing in data science, while two of the co-PIs come from leading academic institutions (Professor Ajit Subramaniam at Columbia University and Professor Pierre Lermusiaux at Massachusetts Institute of Technology). METEOR builds on a legacy of command and control software developed for controlling robotic rovers on Mars as well as long range autonomous underwater vehicles. The PIs have extensive experience in adaptive sampling of oceans and in developing data assimilating models.

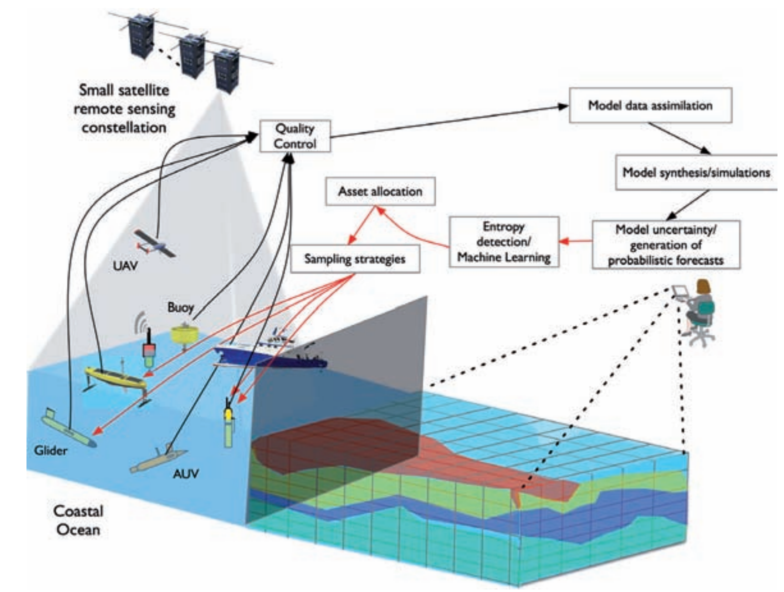

FIGURE 3. METEOR is a collaboration of scientists and technologists across disciplinary and geographic boundaries to envision a new way to observe the coastal ocean, with an emphasis on building a robust software system-of-systems to sense-assimilate-predict-sample with principled methods in engineering of complex systems. The multi-vehicle multi-domain ensemble of robots across space, aerial, surface and underwater domains will observe, collect, assimilate, and learn from data from a range of sensors and platforms to drive and sample in-situ assets to increase model skill over time.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

This project involves computer scientists with expertise in artificial intelligence, engineers with expertise in marine robotics, engineers with expertise in small sat technology development, in addition to field-going observational oceanographers and ocean modelers.

Opportunities for International Participation and Collaboration

There are three non-U.S. PIs in METEOR—João Sousa is a Professor at the Faculty of Engineering, University of Porto, Portugal and is the head of the Underwater Systems and Technology Laboratory (LSTS). Fernando Aguado is an Associate Professor at the University of Vigo and PI of several small sat missions. Joaquín Tintoré is Professor of Physical Oceanography from CSIC (Spanish Research Council) and Director of the Spanish Large-Scale Marine Infrastructure SOCIB (Balearic Islands Coastal Ocean Observing and Forecasting System).

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

We will build a cohort of trans-disciplinary young researchers who will be entrained in using a mix of science and technology from the fields of Integrated multiplatform ocean observation, Artificial Intelligence and Machine Learning, Control Theory, Robotics and Modelling, in the service of understanding coastal ocean processes.

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Measuring the Pulse of Earth's Global Ocean: Ocean Sound and Marine Life Interagency Working Group

Robert P. Dziak, National Oceanic and Atmospheric Administration (NOAA)/Pacific Marine Environmental Laboratory (PMEL); Interagency Working Group on Ocean Sound and Marine Life (IWG-OSML)

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ABSTRACT

The "Measuring the Pulse of Earth's Global Ocean" project will attempt to quantify sound levels in what should be the quietest parts of the ocean—the five deepest locations—to gauge the baseline level of sound in these remote ocean areas. Ocean noise from human-made sources of sound (e.g., shipping) can have a detrimental effect on marine animals that use sound to sense their environment. Thus noise can negatively impact the health of marine ecosystems, which are the basis for many sectors of the global "Blue" economy, including commercial fisheries and aquaculture. This project will gather unique baseline data to monitor the "acoustic health" of the oceans. A novel, deep-ocean capable hydrophone-lander system will be deployed at each of these five deep-sea sites (all >7 km deep). The project will involve the collaboration of several U.S. governmental agencies, private industry and NGOs, and international partners to access these global locations. We will collaborate with scientists from each of these five sites to deploy, recover, and analyze this deep ocean acoustic data. Our ocean sound program aspires to develop a robust and inclusive education/outreach program, focusing on the impact of underwater noise on the health of marine ecosystems.

Vision and Potential Transformative Impact

Accurate locations of the deepest seafloor areas in each of the Earth's five major ocean basins have only recently been determined (Stewart & Jamieson, 2019). We plan to deploy a unique, deep-ocean capable hydrophone-lander system at each of these deep-sea sites (>7 km). Our goal is to make the first, simultaneous measurement of baseline ocean sound levels in what should be the quietest (i.e., lacking human-made noise) locations on Earth. Anthropogenic ocean noise will increase worldwide in the coming decades, as a result of increased container shipping in a growing global economy. High ocean noise levels have a deleterious effect on marine animals and ecosystems, potentially impacting fisheries and other marine economic sectors.

The deepest locations in each ocean are: (1) Molloy Hole, Arctic (5,669 m); (2) Puerto Rico Trench, Atlantic (8,408 m); (3) Java Trench, Indian (7,290 m); (4) Challenger Deep, Pacific (10,925 m); and (5) South Sandwich Trench, Southern Ocean (7,385 m).

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

We will use novel, deep-ocean hydrophone sensors, pressure cases, moorings rated to 11,000 meters depth developed by NOAA-PMEL and several industry partners (High-Tech Inc., Nautilus Marine, Deep-Sea Power & Light, RBR Inc.).

This project will also connect multiple U.S. agencies and departments, including the Navy, Army, Coast Guard, U.S. Geological Survey, Bureau of Ocean Energy Management, NOAA, National Parks Service, National Science Foundation, and Department of State. Also researchers from several academic oceanographic institutions will be involved in the project, including Woods Hole Oceanographic Institution, Scripps Institution of Oceanography, University of Washington, and Oregon State University.

Additional deep ocean mooring/lander technology will require entraining several private sector entities including Teledyne, Kongberg, IcListen, Ocean Sonics & Jasco. Also we will seek partnerships with NGOs (e.g., Ocean Exploration Trust, Caladan Oceanic) to share research vessel time to access these deep-ocean sites.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

The challenges of deep-sea acoustics research will require engagement from diverse sectors of engineering, physics, biology, chemistry, and geology; and expertise from other extreme environments such as volcanoes, deserts, the poles, and even from ocean worlds in the outer solar system (Dziak et al., 2020). Ocean noise from human-made sources of sound can have a detrimental effect on marine animals that use sound to sense their environment, negatively impacting the health of marine ecosystems that are the basis for many sectors of the global maritime, or "Blue" economy, including commercial fisheries and aquaculture. Our ocean sound monitoring will inform conservation efforts nationally and inter-nationally.

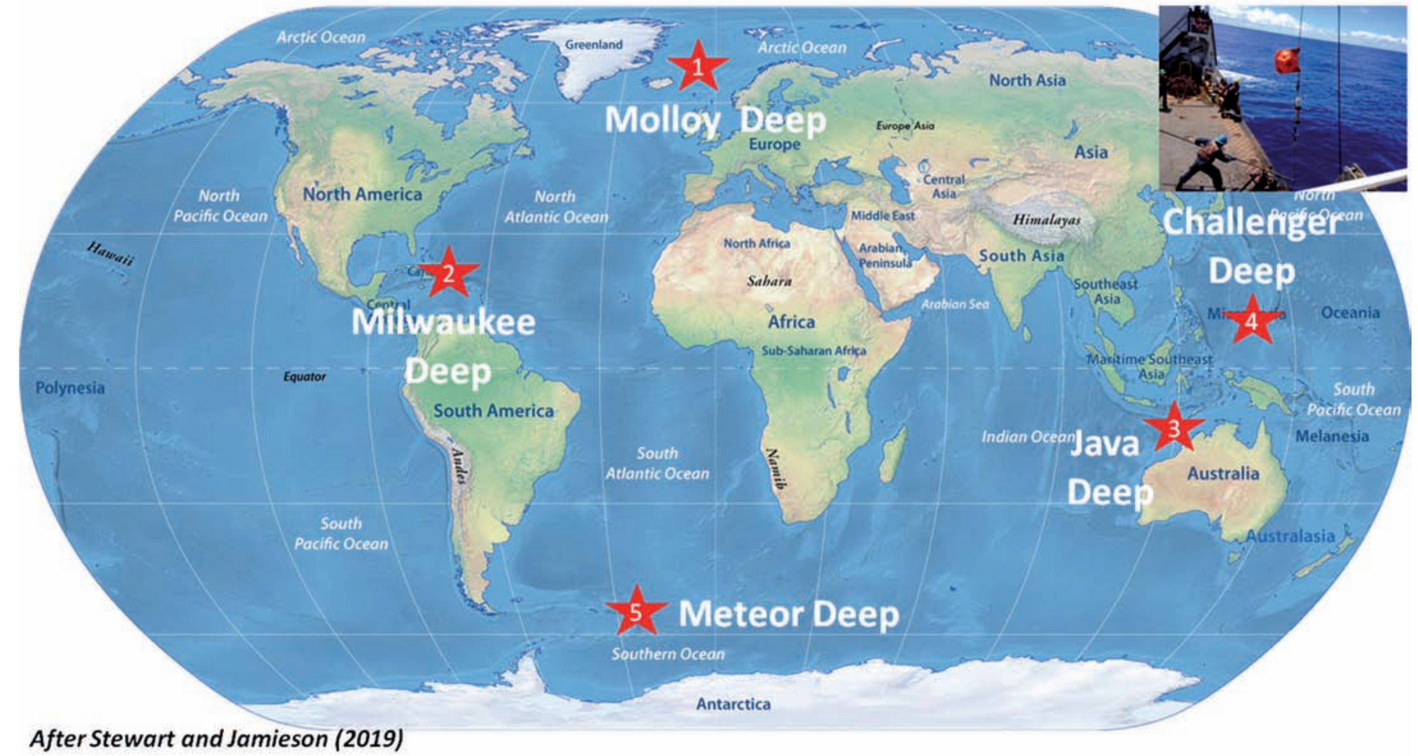

FIGURE 1. Map shows five deepest locations in the world›s oceans, which would be the target for deep-ocean hydrophone deployments. These locations include (1) Molloy Hole, Arctic (5,669 m); (2) Puerto Rico Trench, Atlantic (8,408 m); (3) Java Trench, Indian (7,290 m); (4) Mariana Trench, Pacific (10,925 m); and (5) South Sandwich Trench, Southern Ocean (7,385 m). Depths and locations shown after Stewart and Jamieson (2019). Upper right inset picture shows 2015 recovery of a full-ocean depth hydrophone at Challenger Deep, Mariana Trench (Dziak et al., 2017).

Opportunities for International Participation and Collaboration

Several of the proposed sites are in territorial waters of other countries (Argentina, Greenland, Federated States of Micronesia, Java, and Norway), offering opportunities for collaboration as we work to secure permissions, deploy the hydrophones, and analyze and interpret results. There are also several international ocean sound monitoring organizations (e.g. International Quiet Ocean Experiment, JAMOPANS, International Ocean Noise Coalition) that we will share data with and coordinate global sound level analysis.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Our ocean sound program aspires to develop a robust and inclusive education/outreach component that partners with universities, focusing on Minority Serving-Strengthening Institutions, for undergraduate internship and graduate research programs. Moreover, we seek to engage global academic institutions to develop public outreach programs that work with local schools to build understanding of the impact of human-made underwater noise on the health of marine ecosystems. We also plan to engage with national/international museums and aquariums to create exhibits with our unique deep-ocean sound clips to increase our public outreach and engagement.

Project support provided by NOAA/PMEL Acoustics Program.

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OCEAN DECADE U.S.
U.S. National Committee for the Decade of Ocean Science for Sustainable Development

Envisioning a Global Multi-Purpose Ocean Acoustic Network

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ABSTRACT

Due to the efficient propagation of sound in water, sound in the deep ocean propagates such great distances that soundscapes are influenced not only by local conditions but also by distant sound sources. Ocean Sound is now an Essential Ocean Variable within the Global Ocean Observing System making passive acoustic monitoring routine. Active acoustic probing of the environment informs us about ocean topography, currents and temperature, and abundance and type of marine life vital to fisheries and biodiversity related interests.

Efficient sound propagation is the foundation of a proposed multipurpose acoustic network. Judiciously placed low-frequency acoustic sources transmitting to globally distributed passive acoustic systems provide: (1) high temporal resolution measurements of large-scale ocean temperature/heat content variability using tomography; and (2) underwater geo-positioning (UW-GPS) and communication services enabling basin-scale underwater operation of floats, gliders, and AUVs. Every platform (fixed or moving) equipped with a hydrophone becomes a "GPS" receiver, while listening to the ocean soundscape. The combined active and passive acoustic technology will lead to multi-disciplinary discovery and improved understanding of ocean ecosystem health and biodiversity, climate variability and change, marine hazards, and maritime safety. The same system will improve the operation of gliders, floats and AUVs.

Vision and Potential Transformative Impact

Our vision is a global-spanning multi-purpose ocean acoustic network in direct analogy with GPS that also provides vital information about ocean health, processes, and use. GPS has transformed observation and operation at the earth's surface, and revolutionized geo-positioning (transportation), weather (atmospheric tomography), and early warning (earthquakes). An underwater geo-positioning infrastructure will transform observation and operation in the world oceans. A global underwater system of acoustic sources and receivers enable (1) acoustic geo-positioning for real-time, basin-scale undersea navigation; (2) measurements of large-scale ocean temperature/heat content; (3) ambient ocean sound time series supporting information ranging from marine life distribution to human activity and ocean weather. Passive listening to ocean soundscapes informs us about the physical and bio-acoustic environment from earthquakes to communication among marine life. Passive acoustic monitoring of sound generated and utilized by marine life as well as other natural (wind, rain, ice) and anthropogenic (shipping) sources, has dramatically increased worldwide, enhancing understanding of ecological processes and human ocean use. Acoustic receivers are routinely acquiring data on a global scale; e.g., Comprehensive Nuclear Test-Ban Treaty Organization International Monitoring System (CTBTO) hydroacoustic stations, regional integrated ocean observing systems, gliders (Ocean Tracking Network), profiling floats, and even marine mammals. The true transformation comes from strategically linking independent acoustic systems, projects, and programs into a comprehensive global ocean acoustic network in integration with other systems under GOOS; e.g., ARGO. The value of this network will exceed the sum of each specific system or local system beyond the scope of which it was originally designed.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Global ocean acoustic coverage is realizable. The Acoustic Thermometry of Ocean Climate project, subsequent experiments, and ongoing work in the Arctic demonstrate the value of the data for ocean temperature/heat content, the technology, and no significant impact on marine life (permits routinely required). Hydrophones on moorings and gliders have been acoustically tracked to 60 m and 80 m accuracy, respectively, over 700 km ranges, much better than present day RAFOS subsurface float tracking accuracy of a few kilometers over 2,000-km range. Accurate geo-positioning of ARGO floats will enable real-time continuous tracking (with velocity), while serving as mobile tomography receivers (with joint positioning and sound speed/temperature data assimilation). Within the United States, all the coastal, cabled, and deep sea mooring "nodes" of the National Science Foundation Ocean Observatories Initiative infrastructure with their associated receivers would be brought to bear, as well as other federal assets associated with the Navy, NOAA/NPS Ocean Noise Reference Station Network, and the International Ocean Observing System. Expanding the network with sensors and systems deployed by international researchers in academia, ocean industry, and conservation and management programs provide the necessary elements to achieve full global coverage.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Acoustics is Big Data and all the aspects of that rapidly expanding field would be utilized—data transfer, cloud data and computing, machine learning, AI, and especially the expertise of practitioners. While the state-of-the-art of acoustic source technology is adequate (e.g., the GeoSpectrum low-frequency source as used now in the Arctic), there is room for improvements. The exponentially growing field of optical fiber sensing including distributed acoustic sensing (DAS) will contribute to acoustic array technology. A future sustained ocean observing system needs to be robust and operational, and adaptation and use of industrial offshore technology and infrastructure should be investigated. Submarine cable technology will be brought to bear to support sources and receivers; e.g., SMART Subsea Cables (Science Monitoring And Reliable Telecommunications). Partnerships with industry (shipping, energy, aquaculture) will be critical in achieving global acoustic coverage of the ocean, as the industry sector has a global footprint of activity and assets that could contribute to the global network without detracting from vital business specific drivers or profits.

Opportunities for International Participation and Collaboration

While coordination of ocean acoustic systems and programs can start in the United States, it is inherently an international project requiring contributions from many countries and industries. We expect this to be a significant component of GOOS, just like ARGO, OceanSites, GO-SHIP, drifters, etc. Other international programs could potentially include the CTBTO, International Quiet Ocean Experiment, SMART Subsea Cables, and the European Integrated Arctic Observation System. The proposed Norwegian High Arctic Multidisciplinary Ocean Observing System is a model for building a multi-national, large scale multipurpose acoustic network supporting thermometry, passive acoustics, underwater GPS, and oceanographic measurements.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Specialized training in acoustical oceanography and marine animal bio-acoustics is required to fully take advantage of the Ocean Sound EOV. Evidence of growth in this area is the establishment of acoustics centers and programs both in academia (e.g., UNH, Center for Acoustics Research and Education 2019) and in federal agencies (e.g., BOEM, Center for Marine Acoustics 2020). Additionally, ocean acoustics is a National Naval Responsibility and a focus of Naval STEM activities. Publically available data acquired by a global ocean acoustics network directly supports student and faculty research at US and international universities and agencies to better promote these disciplines.

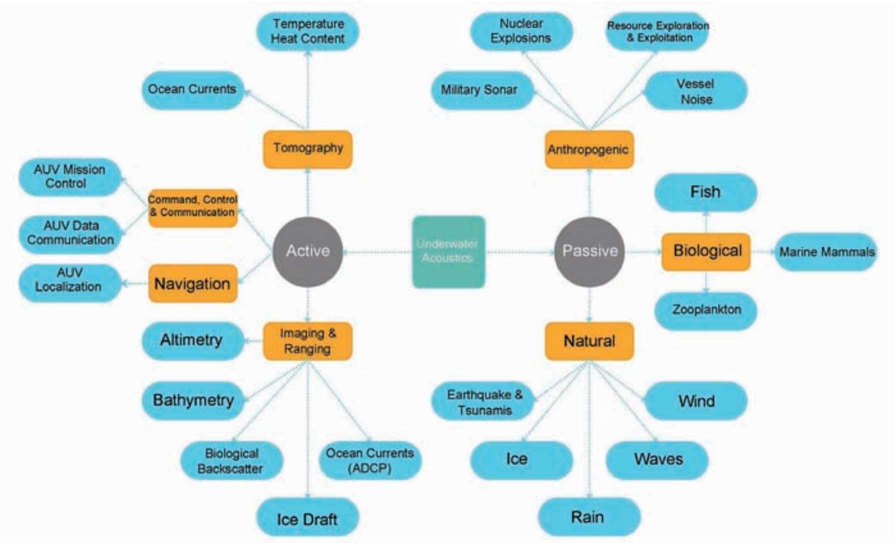

FIGURE 1. Ocean Sound is now a mature Global Ocean Observing System (GOOS) Essential Ocean Variable, which is one crucial step toward providing a fully integrated global multi-purpose ocean acoustic observing system. Ocean observing applications of a multipurpose acoustic system (blue), building on the core observing elements (orange).

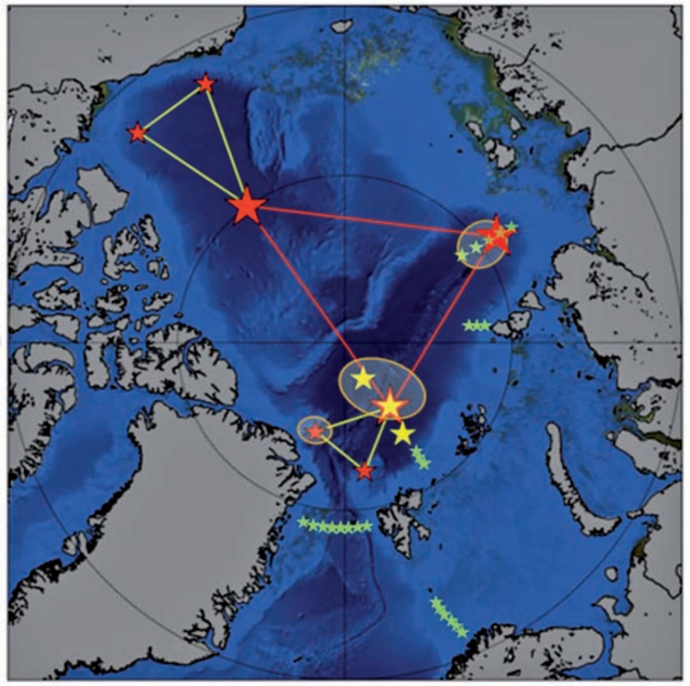

FIGURE 2. The vision of a future multipurpose acoustic network in the Arctic in integration with oceanographic mooring systems as presented in the Norwegian High Arctic Multidisciplinary Ocean Observing System proposal. The acoustic network is proposed to complement the sustained oceanographic moorings which are marked with green star arrays in the Fram Strait, North of Svalbard, and Laptev Sea. To support acoustic geo-positioning, the triplets of sources are implemented in the different regions. The configuration of the three low frequency (~35 Hz) active sources covering the central Arctic are shown with the three largest red and yellow stars. The smaller red and yellow stars indicate mid frequency active acoustic moorings (~250 Hz), which together with one low frequency source forms regional networks in the Beaufort Sea and in the northern part of the Fram Strait. All the acoustic moorings carry passive acoustic sensors for soundscape monitoring and oceanographic instruments providing point measurements supplementing the integrated measurements between the moorings from acoustic tomography.

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Boundary Ocean Observation Network for the Global South

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ABSTRACT

The UN Decade of Ocean Science for Sustainable Development should establish a Boundary Ocean Observing Network (BOON) for the Global South. The BOON is part of the OceanGlider Program which is part of the Global Ocean Observing System (GOOS). The BOON is a network of established timeseries transects collecting long term data sets. Timeseries are critical for making immediate operational decisions and for identifying long term trends of anthropogenic global environmental change. The network has proven important enough to continue observations and expand them. Due to resource and expertise limitations, expanded locations are in similar locations. The UN should build on this success and establish a BOON for the Global South. The same benefits will be garnered by countries and regions that have been missing out. Increased observation coverage will benefit humanity, improving understanding of the Ocean-Climate System, e.g. leading to improved climate prediction models. The UN will facilitate activities to realize a BOON for the Global South including: coordinating local scientists, partnering scientific and technical experts with local scientists, identifying new affordable and easy-to-operate technologies, channeling funds for initial and ongoing costs, and building a framework to continue the BOON-GS long after the Ocean Science Decade.

Vision and Potential Transformative Impact

The Boundary Ocean Observation Network (BOON) is part of the OceanGlider initiative. BOON coordinates existing observation networks at ocean basin boundaries and designates locations for additional timeseries. The desired additional BOON transects are in geographically similar locations to existing lines meaning both observations and researchers will be similar to ongoing efforts. While the program is incredibly useful, more boundary observations in more varied places are needed. The existing program is successful, making it a good example for global expansion.

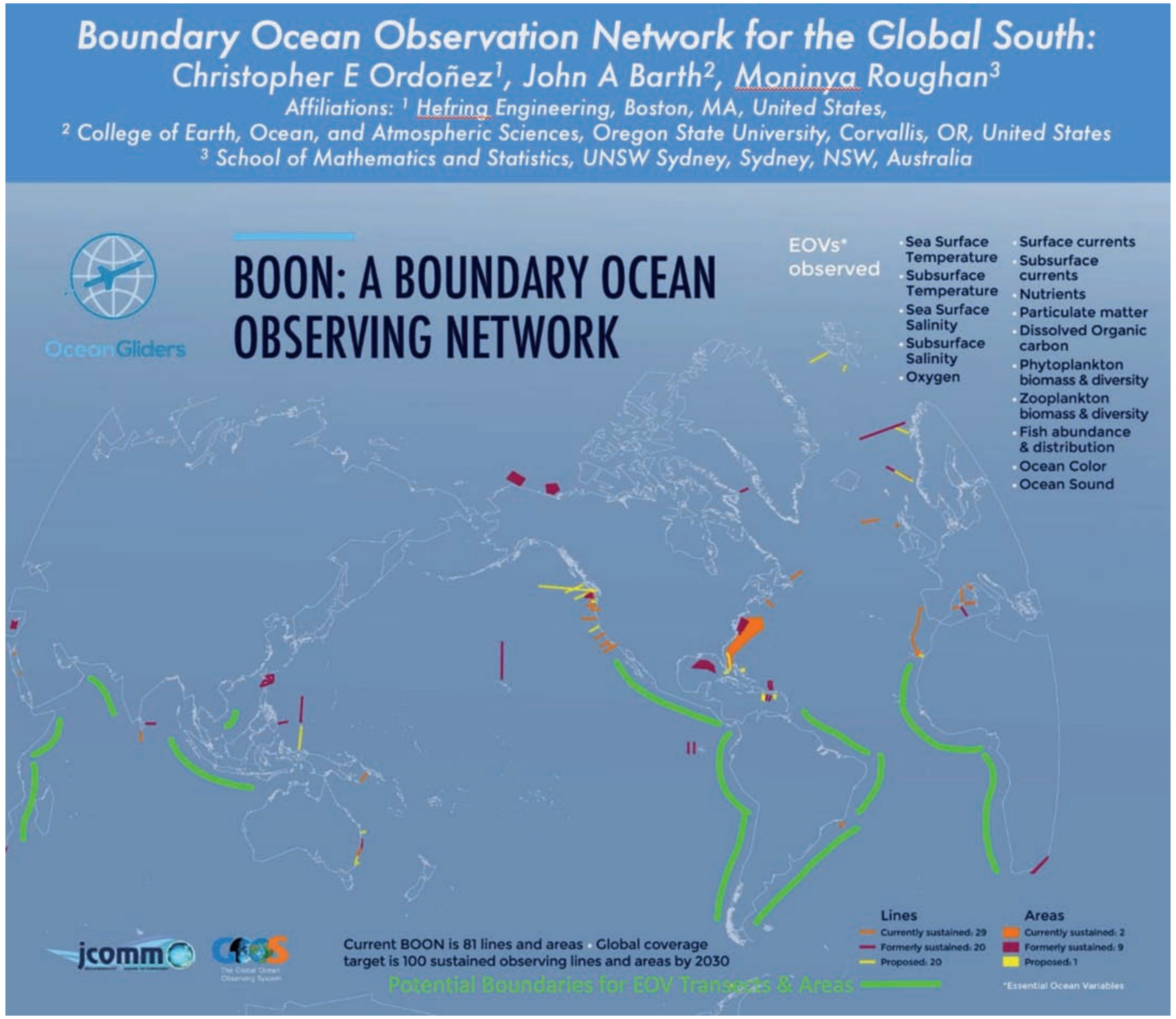
The UNDOSSD should establish BOON-Global South, an observation network across South America, Sub-Saharan Africa, and the Indian Ocean emulating the BOON transects. BOON-GS locations may require varying levels of scientific, technical, and financial assistance. Building capacity will benefit local communities through investment and education. New scientific voices will bring regional knowledge and perspectives into the global conversation. UNDOSSD partners need to 1) establish BOON-GS objectives, locations, & researchers 2) provide local institutional support, 3) identify new technologies to reduce observational costs, 4) connect new researchers with ongoing BOON researchers to overcome technological and scientific challenges, and 5) incorporate BOON-GS data into automated Data Acquisition Centers (DAC), and 6) realize educational opportunities for students from grade school to graduate school.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

BOON-GS is realizable as an extension of the existing BOON program. It has a successful approach. There is a functioning team overseeing the coordination. To make BOON-GS more than just another research opportunity for Western researchers, active and systematic capacity building is required. Capacity building could include: Local/Regional Researcher partnerships with established Research Groups, funding/support for technologies to conduct observations (e.g. underwater gliders, coastal HF radar, etc.), providing a UNLOS ship periodically for more intensive observations. The benefits of the BOON would be recreated for newly incorporated regions, including: integrating BOON-GS researchers into a global community, providing research opportunities for GS academic groups, and building up scientific groups in critical regions where capacity is lacking. In the future, some locations could be selected for a full observatory similar to OOI Endurance Array.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

New ocean observation technologies will need to have lower initial investment costs, present lower maintenance effort, and require less operational personnel. Data handling and data observations will be critical for BOON-GS, but the software expertise can arise from non-ocean sectors. Deployments and recoveries of autonomous vehicles and sensor platforms will require hiring local vessels. The data collected will be of tremendous importance to local communities.



The water mass data will support pollution spill tracking. Ecological data will aid sustainable fishing (e.g. upwelling information) and provide baseline information necessary for establishing marine protected areas. Better understanding of marine ecology, especially as it changes, ultimately promotes food security. Observations can track hazards, such as Harmful Algal Blooms (HABs) and anoxic upwelling events.

Opportunities for International Participation and Collaboration

Three phases of operation each present opportunities for international participation and collaboration. First, setting up the program: identifying research partners and observation locations, identifying key technologies, performing initial baseline data collection including geophysical maps, and procuring technologies. Second, operating the program: helping kick-off operations, supporting data handing & QC, and providing guidance on best practices for maintaining a transect. Third, long-term collaboration: teaming up for multi-region research papers, launching new research efforts based on findings, and integrating new observations & findings into global climate models.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The BOON-GS will build capacity providing new funding, new technology, and new opportunities for scientific researchers and their university students. Several actions can further build capacity. The collected data and the data portal could be utilized in classrooms to help teach mathematics, basic sciences, and introductory earth sciences. BOON-GS Glider deployments could be merged with onboard field trips, similar to Ocean Inquiry Project, which also collect transect data (e.g. water chemistry samples, plankton net tows, etc.). If the research organization facilities become a center of community education with a physical classroom, important environmental information can be disseminated to the public.

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Accelerating Global Ocean Observing:
Monitoring the Coastal Ocean Through Broadly Accessible, Low-Cost Sensor Networks

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ABSTRACT

The global coastal ocean provides food and other critical resources to human societies. Yet this habitat, for which many depend, has experienced severe degradation from human activities. The rates of human-induced changes along the coast demand significantly improved coverage of ocean observations in order to support science-based decision making and policy formation tailored to specific regions. Our proposal envisions developing a global network of low-cost, easily produced and readily deployed oceanographic sensors for use on a wide variety of platforms in the coastal ocean. A substantially large number of these sensors can thus be installed on existing infrastructure, ships of opportunity, and fishing fleets, or even individually along the coast, particularly in vulnerable and disadvantaged regions. This would vastly increase the spatiotemporal resolution of the current data coverage along the coast, allowing greater equitable access. It would also offer significant opportunities for partnership with communities, NGOs, governments, and other stakeholders, as well as a wide range of commercial and industrial sectors to develop and deploy sensors in scalable networks transmitting data in near-real time. Finally, it presents a vastly lowered bar for participation by citizen scientists and other engaged members of the public to address location-specific coastal problems anywhere in the world.

Vision and Potential Transformative Impact

Nearly half of the world's population lives near the ocean, where the concentration of life and human activity provides myriad benefits, including food, jobs, access to navigation, and protection from natural hazards. This densely populated area is changing rapidly and in ways that threaten economies and human health with disease, toxic algal blooms, pollution, frequent storms, and climate-induced loss of resources. Managing and mitigating the impacts of these changes hinges on high-resolution, cost-effective measurements; yet, traditional ocean observations are hampered by high costs and limited resolution.

A key challenge in sustaining accessible and equitable ocean observation is how to make cost-effective measurements and deliver actionable data at relevant spatiotemporal resolutions necessary for illuminating complex system processes and rapidly evolving changes. Development and deployment of low-cost in-situ ocean sensors are critical to address this observational challenge. Having a suite of sensors that are sufficiently affordable and robust enough to be used by scientists, community members, and stakeholders to measure the coastal ocean will revolutionize both ocean science and resource management. We envision implementing low-cost sensor networks in vulnerable coastal regions across the globe to transform ocean observing, predicting impacts from anthropogenic influences, and sustaining the equitable use of marine resources.

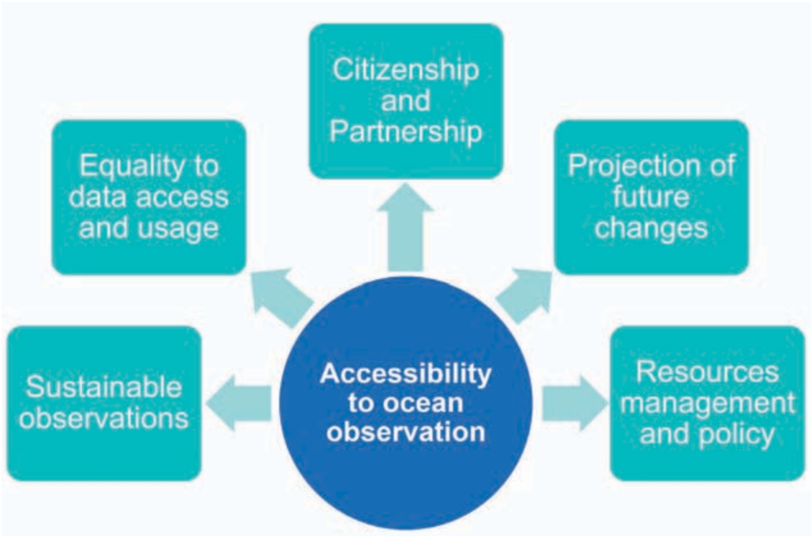

FIGURE 1. Accessibility to ocean observation is a major factor to address many challenges that face the ocean today.

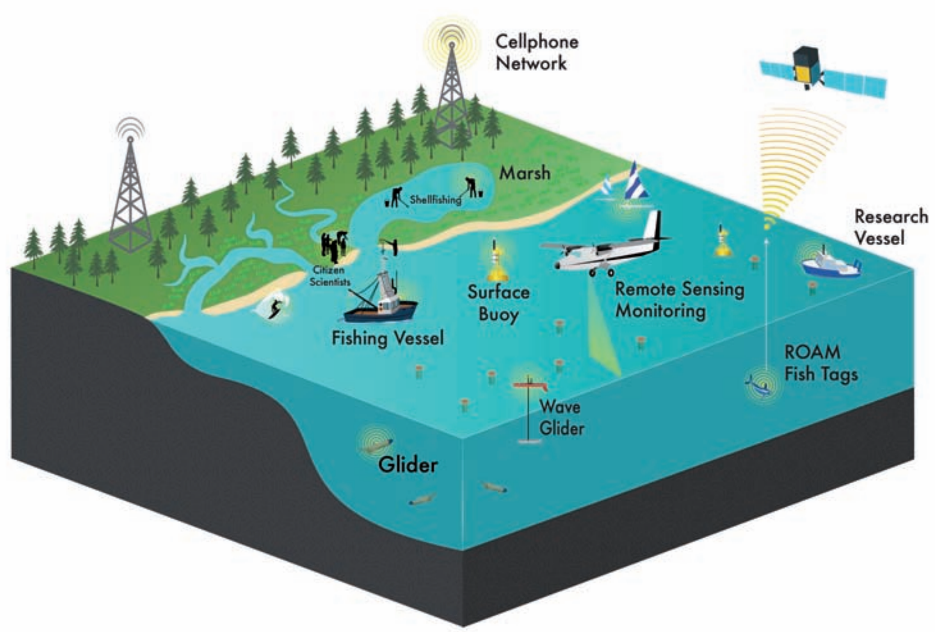

FIGURE 2. Schematic of the conceptual low-cost sensor network in the coastal ocean.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Low-cost sensors can be readily adaptable to current ocean observing infrastructure, such as the Ocean Observing Initiatives (OOI), Argo and Biogeochemical Argo, and the Integrated Ocean Observing System (IOOS) networks, thus substantially improving their observing capabilities. Development and deployment of low-cost sensor technologies also requires significant investments in technology development, academia–private and public–private partnerships, and stakeholder engagement. Citizen scientists may be engaged to deploy and maintain a large number of low-cost, simple sensors providing greater resolution and coverage than ever before. There are ample opportunities to engage ocean industries, such as commercial ships of opportunity and commercial fishing fleets to deploy low-cost sensors worldwide. We also have the opportunity of a pervasive and growing global communication infrastructure, such as cell phone communications and Wi-Fi networks, for transferring large amounts of data collected from low-cost sensor networks in near-real time, significantly increasing the accessibility of ocean observing data for use by the public and decision makers.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Partnerships with other fields engaged in sensor development will enable technologies developed for other applications to be applied to ocean observing. For example, biomedical fields develop miniature sensors that operate within aqueous fluids. Space science requires small, low-power, robust sensors that can operate autonomously to make long-term measurements in harsh conditions. Computer science and engineering will also be critically important for sensor design, incorporating artificial intelligence for data processing and adaptive sampling, and for finding ways to deal with data and computing limitations imposed by transfer of large amounts of data originated from low-cost sensor networks.

Opportunities for International Participation and Collaboration

The development and deployment of low-cost sensors that are capable of monitoring coastal waters and providing immediate feedback to water quality and properties will entail collaboration with global coastal communities to ensure that the data addresses questions of local or regional concern. Partnerships with remote or disadvantaged coastal communities around the globe, such as Indigenous Arctic populations and coastal communities in developing nations, will be key to success, particularly for those whom climate change will disproportionately impact. Other opportunities include international sailing, commercial shipping, commercial fisheries, offshore energy, the tourism industry, and private and public ocean expeditions.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Access to low-cost sensors would enable global, high-resolution measurements analogous in its impact to low-cost sensors that underpin weather forecasting in many parts of the world. Providing international communities with the technology needed to measure the ocean waters near them will entrain a new, globally diverse team and engage them in ocean science and marine resource management, while also training the next generation of ocean scientists. Deployment of low-cost sensor networks will also help developing nations train their workforce and narrow their knowledge gap in ocean sciences and resource management while providing opportunities for technology development, employment, and higher education.

Funding: National Science Foundation; Project Title "Collaborative Research: IDBR: Type A: A High-resolution bio-sensor to simultaneously measure the behavior, vital rates and environment of key marine organisms"; Award Number 1455593 to ZAW and TAM.

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Marine Life 2030: Forecasting Changes to Ocean Biodiversity to Inform Decision-Making: A Critical Role for the Marine Biodiversity Observation Network (MBON)

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ABSTRACT

Marine Life 2030 is a program to establish the globally coordinated system to deliver actionable, transdisciplinary knowledge of ocean life to those who need it, promoting human well-being, sustainable development, and ocean conservation (Figure 1). The diversity of marine habitats and species is fundamental for human survival. Biodiversity provides opportunities for multiple fisheries, the tourism industry, and harbor medicines and materials. The Marine Biodiversity Observation Network (MBON) is the platform to build the community of practice to implement Marine Life 2030. MBON fosters collaborations to coordinate collection, sharing, and application of biodiversity information. Benefits of joining MBON include expanded capacity to address research goals, leveraging resources and best practices; linking natural and social sciences to answer policy questions; engaging diverse and early-career researchers; and addressing issues of concern to humanity.

Vision and Potential Transformative Impact

Marine Life 2030 will establish the globally coordinated system to deliver actionable, transdisciplinary knowledge of ocean life to those who need it, promoting human well-being, sustainable development, and ocean conservation. The Marine Biodiversity Observation Network (MBON) is the platform to build the community of practice needed to implement Marine Life 2030.

The diversity of marine habitats and species is a fundamental characteristic of marine ecosystems (Figure 2). Groups of species can maintain ecosystem functions like the cycling of nutrients including carbon and nitrogen, provide opportunities for multiple fisheries, support the tourism industry, and harbor medicines and materials. To address these needs, MBON seeks to (1) measure, monitor, and forecast changes in marine biodiversity, (2) understand natural and human-related causes including effects due to climate change, and (3) assess and predict how those changes affect ecosystem function and services over various spatial and temporal scales. Given the challenges in applying marine biodiversity observations to inform conservation and management decisions, MBON will leverage its trans-disciplinary, inclusive framework to build stronger connections with stakeholders involved in "on-the-water" decision making so that observations of marine biodiversity are directly integrated into decision making. This framework is necessary to address all of the Ocean Decade Challenges and achieve the ambitious goals traced for the decade.

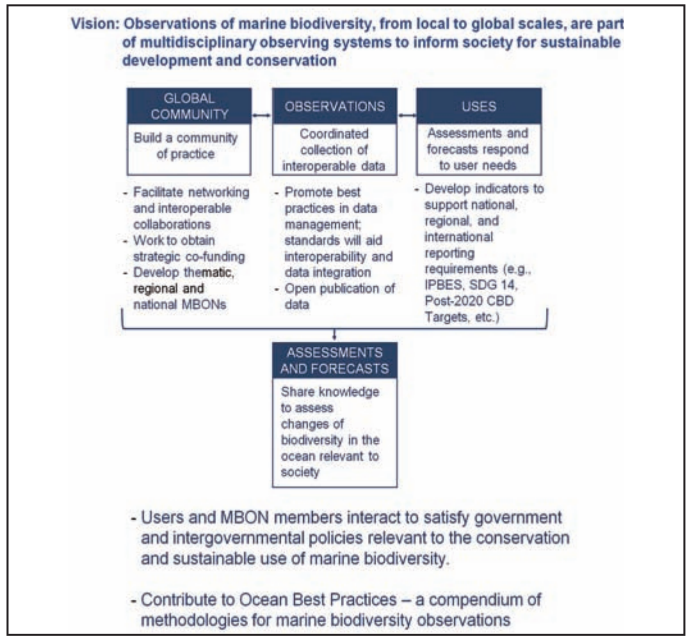

FIGURE 1. MBON Vision: Observations of marine biodiversity, from local to global scales, are part of multidisciplinary observing systems to inform society for sustainable development and conservation. (Drawing inspired by Amanda Bates.)

FIGURE 2. Schematic of a complex food web that supports human uses and of different technologies for observing life in the sea. (Drawing by Kelly Lance inspired by Francisco Chavez, courtesy of MBARI).

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Marine Life 2030 will develop linkages between government agencies, non-governmental organizations, the private sector, and academia, building on the MBON established through the National Oceanographic Partnership Program (NOPP) and advancing the legacy of the Census of Marine Life. It coordinates among national and international groups to integrate critical biological observations into ocean observing, mapping, exploration, characterization, and forecasting strategies and programs.

The Marine Life 2030 framework is fundamental to meet the U.S. needs for ocean policy and for executing Ocean Decade Actions including:

- Mapping resources of the U.S. EEZ as mandated in the federal National Ocean Mapping, Exploration, and Characterization (NOMEC) plan, across disciplines, in four dimensions (horizontally and vertically from seabed to surface, watershed to the ocean interior, and in time).
- Assessing biodiversity value for societal benefit.
- Advancing ecological forecasting and applications.
- Emerging approaches for biodiversity assessment and research (including eDNA, imaging, acoustics, movement, AI, remote sensing).
- Expanding capacity, literacy, participant diversity, and use of traditional knowledge for inclusion and representativeness.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Adaptive management strategies and monitoring requirements for public and industry sectors depend on information on status and trends of marine biological resources. This information is not yet consistently available at regional or global scales. Biodiversity indicators for advancing overlapping ocean uses and conservation need a foundation of standardized approaches and interoperable data. MBON enables user-accessible products based on novel technologies and their integration, including environmental DNA, remote sensing, imaging, acoustics, and citizen science. This informs national to inter-national stakeholders and indicators of the UN Sustainable Development Goals, Ramsar Convention, global biodiversity assessments (IPBES), and fisheries treaties.

Opportunities for International Participation and Collaboration

MBON fosters collaborations to coordinate collection, sharing, and application of biodiversity information. It contributes to international Research Coordination Networks, Scientific Committee on Oceanic Research (SCOR) Working Groups, Global Ocean Observing System (GOOS), Ocean Best Practices System, Ocean Biodiversity Information System (OBIS), Ocean Teacher Global Academy, Group on Earth Observations (GEO BON, Blue Planet), the Global Ocean Acidification Observation Network (GOA-ON), MarineGEO, academia, and organizations (e.g., UNEP WCMC) to inform research and policy. An MBON Ocean Decade Program will expand present Actions for capacity exchange with small island developing states and developing nations through training workshops, webinars, publications, and fundraising.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

MBON is a network of people that leverages the expertise, interests, and focus of groups across national and international networks to engage students and early-career professionals of diverse ethnic and national groups, backgrounds, and gender. A goal is to share standards, best practices and approaches for interoperability and knowledge management and exchange. This includes advancing ethics, diversity, and inclusion among stakeholders. MBON has been holding workshops on new tools for data sharing weekly to monthly for multiple international collaborators and seeks Ocean Decade Actions under Marine Life 2020.

Funding: NOAA, BOEM, ONR, NSF, NOPP, NASA Applied Sciences Office,Biodiversity & Ecological Forecasting Program; National Science Foundation (Co-PI J. Pearlman). OceanObs Research Coordination Network (OCE-1728913) to FMK and JP. NASA: Dynamic seascapes to support a biogeographic framework for a global marine biodiversity observing network, 80NSSC18K0412; and NASA : Marine Biodiversity Observing Network in the Northern California Current: Understanding Patterns and Drivers of Biodiversity and Ecosystem Functioning from Plankton to Seascapes, 80NSSC20M0008 to MTK. NOAA/IOOS #NA16NOS0120018 to BK. NSF OCE-1829922, "Collaborative Research: The role of a keystone pathogen in the geographic and local-scale ecology of eelgrass decline in the eastern Pacific" to ED. NOAA, Cooperative Agreement NA19NOS0120198, A Sustainable, Integrated Arctic Marine Biodiversity Observing Network to LWC, KI and JG. NASA, Biodiversity and Ecological Forecasting Program (grant NNX14AR62A); the Bureau of Ocean Energy Management, Environmental Studies Program (BOEM Agreement MC15AC00006); and NOAA in support of the Southern California Bight Marine Biodiversity Observation Network to RM. NASA Applied Sciences, Ecological Forecasting Program, Grant# NNM11AA01A to ME. NOAA IOOS SCCOOS Award: #NA16NOS0120022 to CA. NOAA (NOPP); Implementing a Marine Biodiversity Observation Network (MBON) in South Florida to Advance Ecosystem-Based Management; N00014-18-S-B007 to NH. NOAA IOOS NANOOS Award: #NA16NOS0120019 to JN. NASA: Grant 80NSSC18K0318, "Laying the foundations of the Pole-to-Pole Marine Biodiversity Observation Network (MBON) of the Americas" to EM. US MBON Gulf of Maine project to NERACOOS (NOPP award NA19NOS0120197) and BOEM Cooperative Agreement M19AC00022 to the University of Maine. NASA, The CeNCOOS MBON, 80NSSC20M0001; NOAA, CeNCOOS Partnerships, NA16NOS0120021 to FC.

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Persistent Mobile Ocean Observing: Marine Vehicle Highways

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ABSTRACT

Persistent mobile ocean observation platforms, supported by arrays of subsea marine vehicle service stations, will enable direct study of oceanographic and geological processes that, due to their transient nature and spatiotemporal variability, are not well understood. These include, but are not limited to, ocean–seafloor interactions and crustal ecosystems, mid-ocean ridge volcanism, coastal circulation and shelf ecosystems, reef health, and arctic sea–ice interaction. Further, certain types of subsea events, such as erupting submarine volcanoes, instabilities in methane hydrate deposits, marine mass-wasting events, turbidite flows, the ecological impacts of major earthquakes, breaking internal waves, the fate of mid-water vortices, and episodes of anoxic upwelling, can be energetic, transient, and unpredictable, often having unverifiable consequences. These cannot be readily detected, characterized, or quantified owing to the difficulty of anticipating the onset of such phenomena. The intractability of launching major sea-going assets with short lead times to capture and document such evanescent system-level processes from beginning to end means that our understanding of these and related processes is not readily expandable with current oceanographic tools.

Marine Vehicle Highways (MVHs) will change the way ocean science is conducted by making temporally and spatially distributed data sets more attainable and accessible, opening the door for broader participation in transformative ocean science.

Vision and Potential Transformative Impact

Marine Vehicle Highways (MVHs) are envisioned as arrays of subsea vehicle "service stations" deployed along routes of observational interest: following coastlines, spanning across ocean basins, or along the mid-ocean ridge. Each service station has a power and communications source, such as an observatory cable or a marine energy harvesting system, and a standardized vehicle interface supporting battery charging and vehicle-to-shore communication. Any vehicle with a compatible interface can "dock" at the service station, recharge, upload data, retrieve mission updates, then resume observations. MVHs will support autonomous vehicles as they conduct long-range monitoring missions or local operations, becoming "resident" for extended periods near one or more service stations. MVHs will also be key enablers of dense arrays of geophysical instruments by supporting data (and possibly power) shuttling between fixed seabed instruments and the closest service station, allowing for long-term instrument deployments without vessel-supported intervention.

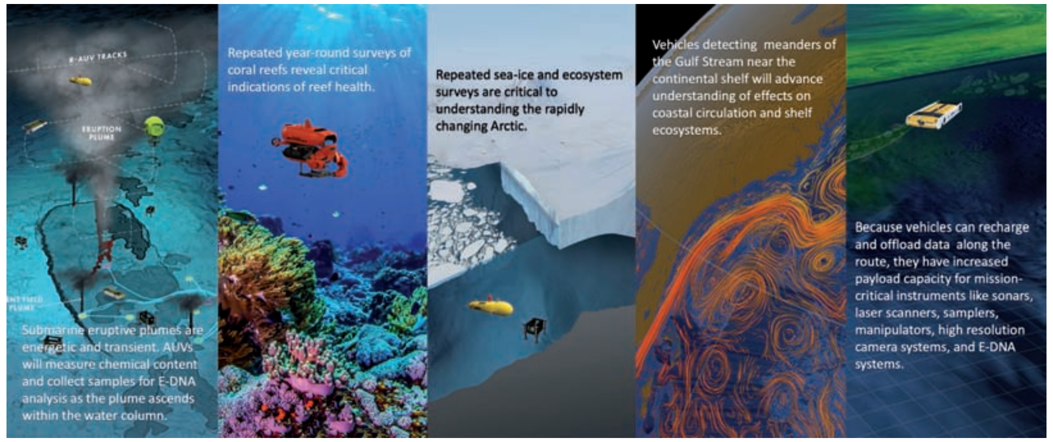

FIGURE 1. A subset of potential applications for remote marine vehicles supported by service stations on Marine Vehicle Highways (MVHs). MVHs will provide recharging and vehicle-to-shore communications, allowing vehicles to transit to and operate in remote areas without support from manned vessels.

A service-station-compatible fleet of vehicles with customizable payloads will augment the system further, allowing innovative researchers to focus on measurement technologies rather than vehicle dynamics. With charging available through service stations, vehicles will support payloads requiring higher power demands, such as sonars, cameras systems, and E-DNA samplers.

MVH infrastructure will transform ocean science by supporting a persistent mobile ocean sensing presence that does not rely upon costly and weather-dependent manned vessel operations. Transient events and processes, previously unobserved, will be closely monitored by remote assets while collected data is pushed in near-real time to shore, allowing any operator with an Internet connection to analyze and re-task vehicles anywhere in the world.

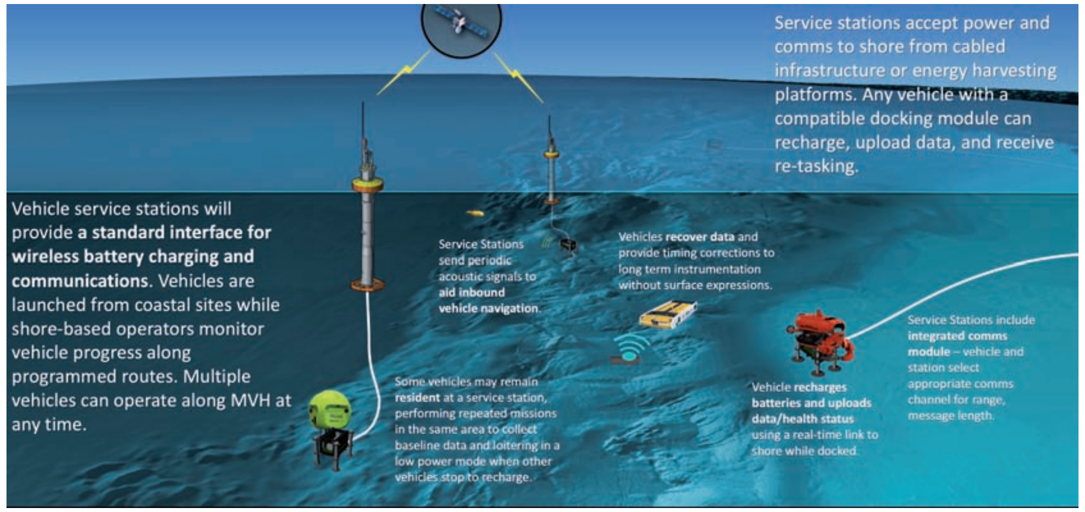

FIGURE 2. A conceptual image of the diverse robotic ecosystem supported by Marine Vehicle Highways.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The technical elements required to develop MVHs exist. Cabled observatories, like the NSF's Ocean Observatories Initiative Regional Cabled Array and the Monterey Accelerated Research System (MARS) offer ideal testbeds with sufficient power and real-time communications for marine vehicle service stations. Meanwhile, the technologies that harvest energy from the ocean's waves and tides are maturing and will provide options for easily deployed power stations virtually anywhere in the World Ocean while a growing satellite fleet supports remote communications around the globe.

Establishing a standard power and communications docking interface module will take advantage of developments in commercial underwater wireless power transfer technologies as well as acoustic, optical, and RF data links. Public–private partnerships will play a key role in identifying and codifying interface standards. Meanwhile, vehicles capable of routine docking will be hardened for long-term deployments, drawing from industrial inspection and intervention vehicle development as well as both public and private efforts in robotic autonomy.

Persistent, mobile, and scalable ocean observation systems are key to developing a predictive understanding of oceanic processes, and will provide a new way to observe critical transient phenomena that often go undetected in our global ocean.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Outside of traditional ocean sciences, this work will engage the following sectors:

- **Marine Energy**—will provide flexible options for powering remote vehicle service stations throughout the global ocean
- **Robotics**—will enable near-field perception and autonomous docking as vehicles move into and out of service stations, novel vehicle applications, service station monitoring and scheduling
- **Data Science**—will inform data recovery, analysis, and the generation and dissemination of data products
- **Submarine Cables**—will provide power and high bandwidth communications to service stations

Installed MVHs will be useful beyond research, able to support operations within the larger Blue Economy. For example, commercial operators of offshore systems may take advantage of service stations, using them to charge and transmit data collected by vehicles supporting subsea operations or monitoring environmental compliance.

Opportunities for International Participation and Collaboration

This ocean shot affords significant opportunities for international participation and collaboration:

- Scientific collaboration to determine high-priority MVH "routes" and sensing modalities (water sampling, mapping, etc.)
- International standards development for service station interfaces
- Open standards will lead to innovative vehicle and payload development
- Service station arrays may link subsea routes between nations, promoting collaboration on system and vehicle maintenance
- International cabled observatories serve as system development testbeds and vehicle qualification sites

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Marine vehicle highways build spatial and temporal ocean observing capacity by providing unprecedented mobility and persistence. While existing high-persistence autonomous measuring systems, such as Argo floats and buoyancy-driven gliders have limited payload capacity, the ability for vehicles to recharge at sea opens opportunities for enhanced payloads, as well as flexible and rapid response times to transient underwater events. These capabilities give scientists an advanced toolbox for studying and understanding interconnected ocean processes, especially within the water column and at the water/seabed interface, that has never before been attainable.

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Improved Value of the Observing System Through Integrated Satellite and In-Situ Design

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ABSTRACT

Primary among the goals for this Ocean-Shot will be to support the important role of, and maintenance of the continuity of space-based, broad-scale measurements of the essential ocean surface variables; e.g., OSVW, SSH, SST, SSS, Precipitation, Ocean Color, by building on associated in-situ measurements. Projects and pilots will seek to enhance the value of satellite observation with measurements made of physics, biogeochemistry, and biology within the water column, and the atmosphere. This endeavor will also contribute to the well-established infrastructure in place to improve the calibration, evaluation, and validation of satellite measurements, and to intercalibrate different satellite missions and instruments. This project will highlight community awareness of the interfaces and activities that will ensure the sustained observations needed for EOV satellite and in-situ observational operations, research, and monitoring.

Activities will include convening and/or joining an international, multidisciplinary working group or groups consisting of members of requirements setting, implementation teams, and data managers. In time the project will develop a series of use cases highlighting satellite field campaigns that have resulted in enhanced system design and to an improved understanding of the ocean. Over the decade the project will seek to create mechanisms resulting in ongoing recommendations for additional co-design requirements among the scientific, remote sensing, and in-situ community.

Vision and Potential Transformative Impact

The goal of this Ocean-Shot is to demonstrate the value of improved satellite and in-situ observing system design through globally increased measurement resolution and concerted progress toward a coupled Earth system estimation. Primary in its function will be to maintain continuity of space-based, broad-scale measurements of the essential ocean surface variables (OSVW, SSH, SST, SSS, Precipitation, Ocean Color) by building on associated in-situ measurements. Outcomes will make the community more aware of the interfaces and activities that will ensure the sustained observations needed for combined satellite and in-situ observational operations, research, and monitoring.

Beyond the well-established infrastructure in place to improve the calibration, evaluation, and validation of satellite measurements, and to intercalibrate different satellite missions and instruments, these activities will seek to enhance the value of satellite observation with measurements made of physics, biogeochemistry, and biology within the water column, and the atmosphere. An important contribution will be to evaluate and highlight projects and studies that may lead to potentially reconfigured in-situ systems and networks that are able to address the evolving needs of the observing system and reflect new knowledge.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Outcomes will have the long-term benefit of contributing to the emerging understanding of global ocean change studies generated by modeling programs (an example in the United States is the NASA ECCO program, which estimates ocean circulation and its role in climate, combining ocean circulation models with global ocean data sets). During the next decade, focus will be on sea-level impact from polar ice sheets, and the increased use of biogeochemical and ecosystem data to constrain global cycles of carbon, nitrogen, and oxygen. Activities will include the review of pilot and process studies created to guide future design using the most effective combination of platforms and technologies. Field campaigns will include enhanced in-situ observation with an emphasis on climate regimes, and variables needed to better estimate surface heat and freshwater fluxes, specific dynamic biogeochemical and biological regions, extend observation resolution in polar regions, regional seas, and in the equatorial band.

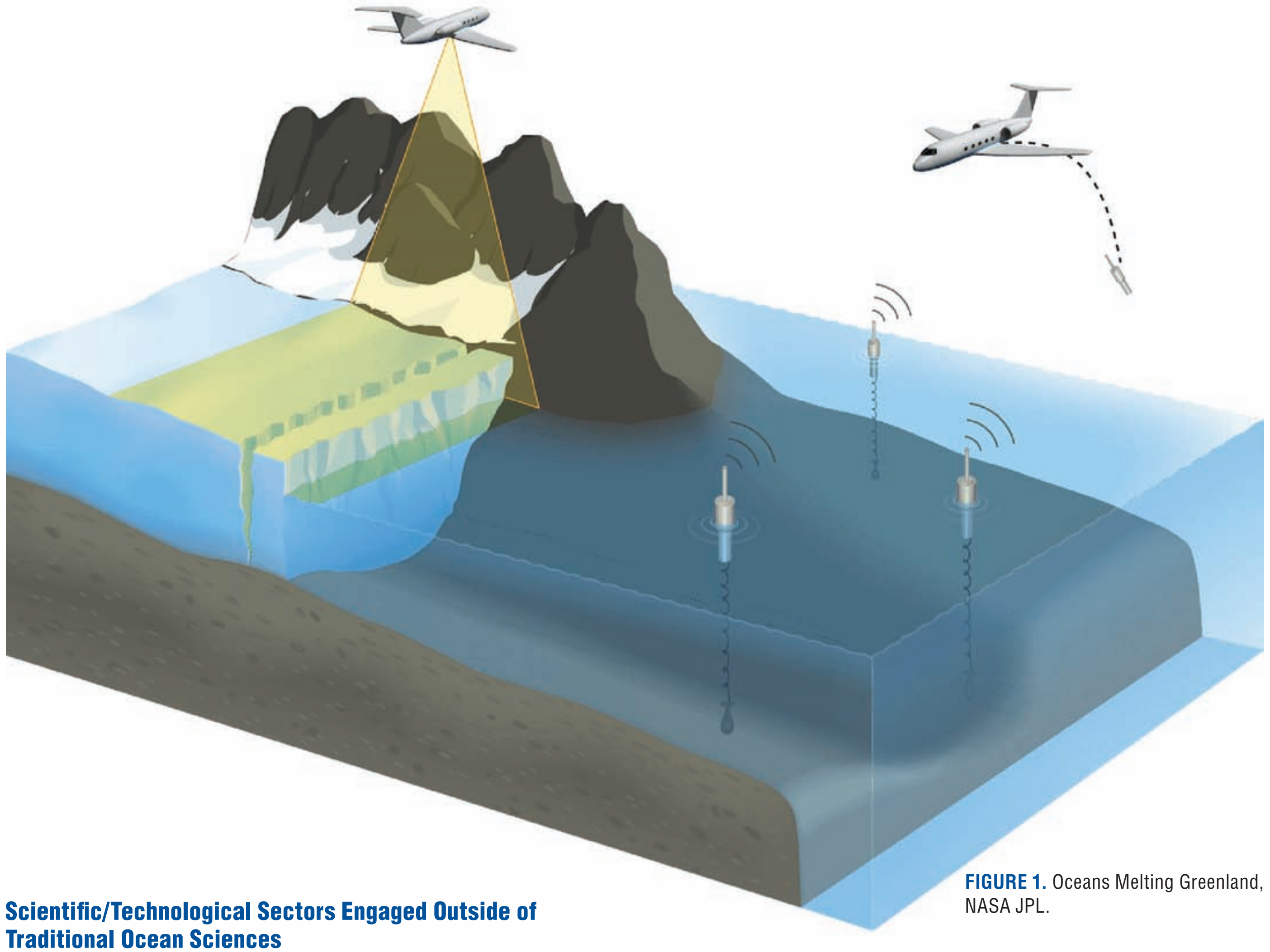

FIGURE 1. Oceans Melting Greenland, NASA JPL.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

The current ocean observing system contributes to not only the understanding of climate variability and change, but also to a wide variety of services including weather and seasonal-to-interannual forecasting, living marine resource management, and marine navigation. Through three decades of sustained satellite and in-situ observations, there have been significant contributions to an improved understanding of the ocean's role in the Earth system, including a better understanding of global and regional sea-level change. Improvements are needed in order to enhance current model capability and to develop coupled modeling systems. This includes greater resolution of long-term observations that improve the understanding of climate variability and change, and other services that underpin national defense, economic, and social policy decisions.

Opportunities for International Participation and Collaboration

Satellite missions have a long history of effective international collaboration that is necessary in order to coordinate mission efforts and capabilities. Similarly, international groups such as GOOS promote international cooperation to sustain the ocean observing system. However, there exists a gap among activities focused on combined satellite and in-situ requirements setting and system design. The decadal goal will be to generate synergy among agencies for the analysis and design of sensor platforms, and multidisciplinary integrated virtual constellations that observe at higher resolution than what can be observed solely from space.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Over the decade, this work will demonstrate the value of sustained remotely sensed data to the global ocean observing system and how uncertainties can be overcome through better informed system design. This will require contributions from the scientific community working at many levels. Initially this activity will build from a focus on field campaigns currently supported by NASA (e.g., Oceans Melting Greenland: https://omg.jpl.nasa.gov/portal/; and S-MODE: https://espo.nasa.gov/s-mode/content/S-MODE) that can readily be used to pilot this approach. This will then be applied to other field studies and pilot projects conducted by other U.S. stakeholders and beyond. As this step-change in observing system capability and functionality matures, it will provide new scientific and analytic opportunities across the many scientific and societal disciplines impacted by ocean observations.

Relevant Ocean Decade Challenge(s):

- **Challenge 7:** Ensure a sustainable ocean observing system that delivers timely data and across all basins
- **Challenge 8:** Develop a comprehensive digital representation of the ocean
- **Challenge 9:** Ensure comprehensive capacity development and equitable access to data, information, knowledge, and technology

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Transformative Ocean Observing for Hurricane Forecasting, Readiness, and Response in the Caribbean Tropical Storm Corridor

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ABSTRACT

The upper ocean in the Western Tropical Atlantic tropical storm corridor—including the Caribbean Sea—is under-sampled and climatologically warming (Figure 1). Regionally varying Essential Ocean Features impacting tropical cyclone dynamics include fresh water upper ocean layers, mesoscale eddies, high Upper Ocean Heat Content values, and inflows from the Subtropical and Equatorial Atlantic. Ongoing research indicates that hurricane intensity forecasts can be improved with expanded and sustained ocean data collection and utilization along the hurricane path.

This proposed activity will build supporting physical and social infrastructure and conduct a long-term sampling program in this critical region using gliders, High Frequency Radars (HFR), and developing technologies to provide real-time information resulting in hurricane forecast improvement. Improved forecasts will support new generation of local storm surge/precipitation/wave and coastal impact models and guidance used to directly enhance resilience.

The success of this project will depend on the merger of regional scale planning and management AND development of local-level partnerships for implementation. To be sustainable, operational, analytical, and actionable, capability has to exist at the multiple proposed regional system nodes. We will promote expanded education and workforce development using existing partner capabilities, and include an Ocean Observing for SIDS/Developing Economies component. Product and information delivery systems will have local interpretive support and will incorporate local knowledge and expertise.

It is our hope that by 2030 our legacy would be successful program to—in the words of the Decade Action Framework—"sustain long-term high-quality **observations** of marine and coastal environments including human interactions and deliver **forecast and decision-support tools**."

Vision and Potential Transformative Impact

Recent annual U.S. economic losses from hurricane-related damage is $112B/year—and climbing—with 1,095 deaths/year. Studies indicate that hurricane intensity forecasts can be improved with expanded and sustained ocean data collection and utilization along the hurricane path.

The upper ocean in the Western Tropical Atlantic tropical storm corridor is under-sampled and climatologically warming. Regional Essential Ocean Features impacting tropical cyclone dynamics include fresh water layers, mesoscale eddies, high Upper Ocean Heat Content values, and Atlantic inflows.

This activity will build supporting physical and social infrastructure and conduct a long-term sampling program in this critical region using gliders, HFR, and developing technologies to provide real-time information resulting in hurricane forecast improvement. Improved forecasts will support new generations of local coastal impact models and guidance used to enhance resilience.

To be transformative, this effort will:

- Strive for appropriate observation density, diversity, and utilization for a sustained, meaningful U.S. and regional impact;
- Create a regionally distributed supporting infrastructure including operations, education, training, and workforce development;
- Engage a diverse and influential group of partners to convert forecasts to products to local action;
- Lead to a sustained, expanded, regional Ocean Observing System based on GOOS principles.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Existing smaller scale projects provide proof of concept scale examples. These include ongoing U.S. Hurricane Glider missions; HFRs in Puerto Rico & Mexico; and research into assimilating these data into ocean models for hurricane forecasting.

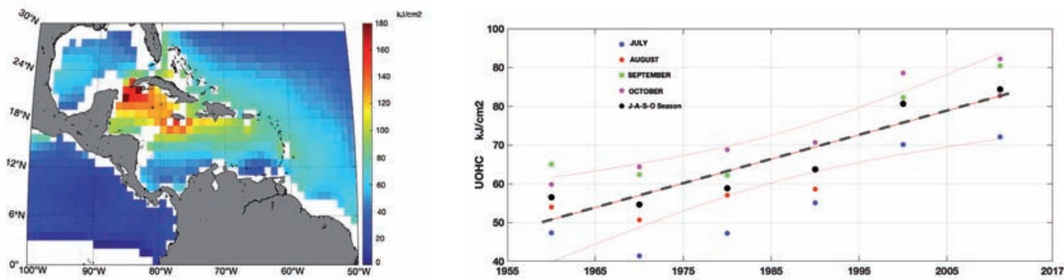

FIGURE 1. Critical Essential Ocean Feature (upper ocean heat content) for hurricane intensification is STRONG and STRENGTHENING. (Left) Mean upper ocean heat content in kJ/cm². From World Ocean Atlas WOA18 Period 2005–2017 Hurricane Season (July–August–September–October). (Right) Caribbean-wide upper ocean heat content Hurricane Season (July–August–September–October), Linear Trend = 0.62 kL/cm²/Year. World Ocean Atlas WOA18 decadal data.

Existing and potential connections to expand the project scope:

- U.S. IOOS Regional Associations: CARICOOS, as well as GCOOS, SECOORA, IOOS/COMT.
- NOAA–OAR Global Ocean Monitoring and Observation Extreme Events Ocean Observing Task Team; AOML PHOD, HRD; Cooperative Institutes; NHC, NCEP, HFIP
- Naval Oceanographic Office, Naval Research Lab collecting data and developing models
- Universities—Rutgers, Texas A&M, University of Puerto Rico, UVI, many others
- National Academies
- Technology Development—an opportunity for new glider, autonomous vehicle deployments (private, CENOTE, NOAA UxS)—especially lower cost, easily deployable, extended vertical measurement, as well as integration of ocean observing technologies designed for developing economies and SIDS.
- Foundations—International Glider missions are already under way funded by the G Unger Vetlesen Foundation; other opportunities will be explored.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

An inspiration for this activity was a MacArthur Foundation "100&Change" proposal (https://macarthur100.marine.rutgers.edu) led by Rutgers University, including TAMU and UVI. Thinking broadly about how to fund a project of this scale and societal impact requires expanding into nontraditional partners, including:

- Economic Support/Investment entities (Development Banks, foreign aid, EU, etc.)
- Tourism/Hotel/Cruise industries
- Insurance/Reinsurance industry
- Corporate charitable foundations
- Visualization/Products/Data

Opportunities for International Participation and Collaboration

This project is a component of a wider regional UN Decade Program being proposed for IOC endorsement in collaboration with IOCARIBE, the IOC SubCommission for the Wider Caribbean, which will help access to many regional partners. Other International partners are expected to include:

- Regional IOCARIBE member states, including the United States, United Kingdom, France, and Netherlands, and the European Union. IOCARIBE has passed a resolution at IOCARIBE XV and XVI urging member states contributions. The project is being promoted through the Western Tropical Atlantic Safe Ocean Working Group.
- UK Commonwealth Marine Economies Programme (CMEP)
- Other UN-related organizations including WMO, JCOMM, UNEP, ICG/CARIBE-EWS
- Regional economic, environmental and emergency response bodies (OECS, CDERA, CEPREDENAC, 5Cs, CIMH)
- National Environmental, Marine, and Meteorological Agencies
- Regional Universities (CICESE, UWI, UNAM)
- Regional Observing/Science Organizations (e.g., ATLANTOS, POGO, GEO Blue Planet)

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers and Technologists

The success of this project will depend on the merger of regional scale planning and management AND development of local level partnerships for implementation. To be sustainable, operational, analytical, and actionable capability has to exist at the multiple proposed regional system nodes. We will promote expanded education and workforce development using existing partner capabilities, and include an Ocean Observing for SIDS/Developing Economies component. Product and information delivery systems will have local interpretive support and will incorporate local knowledge and expertise.

As an example/model, in 2004 the Caribbean Sea had ONE non-U.S. operational real-time sea level gauge. A visionary push inspired by a commitment to a regional tsunami warning system has raised the present number to 45, with over 30 countries locally trained and actively participating.

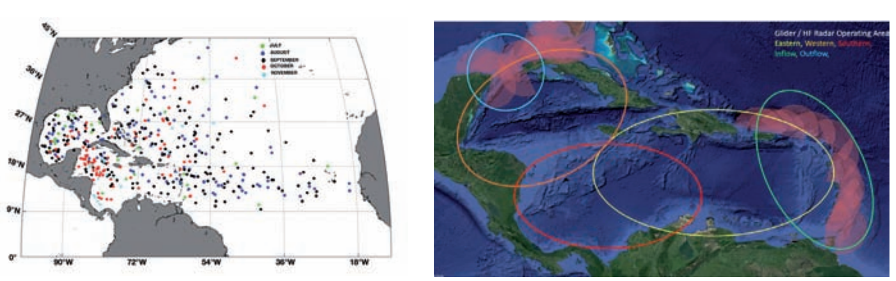

FIGURE 2. Locations of rapid intensification and proposed operational assets. (Left) Site of storm rapid intensification (defined as > 30 kt increase in 24 hours). Based on HURDAT2 (1851–2019). (Right) Possible HF radar and glider operating areas for monitoring Caribbean regional essential ocean features.

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Twilight Zone Observation Network:
A Distributed Observation Network for Sustained, Real-Time Interrogation of the Ocean's Twilight Zone

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ABSTRACT

The ocean's twilight zone (TZ) is a vast, globe-spanning region of the ocean. Home to myriad fishes and invertebrates, mid-water fishes alone may constitute 10 times more biomass than all current ocean wild-caught fisheries combined. Life in the TZ supports ocean food webs and plays a critical role in carbon capture and sequestration. Yet the ecological roles that mesopelagic animals play in the ocean remain enigmatic. This knowledge gap has stymied efforts to determine the effects that extraction of mesopelagic biomass by industrial fisheries, or alterations due to climate shifts, may have on ecosystem services provided by the open ocean. We propose to develop a scalable, distributed observation network to provide sustained interrogation of the TZ in the northwest Atlantic. The network will leverage a "tool-chest" of emerging and enabling technologies including autonomous, unmanned surface and underwater vehicles and swarms of low-cost "smart" floats. Connectivity among in-water assets will allow rapid assimilation of data streams to inform adaptive sampling efforts. The TZ observation network will demonstrate a bold new step towards the goal of continuously observing vast regions of the deep ocean, significantly improving TZ biomass estimates and understanding of the TZ's role in supporting ocean food webs and sequestering carbon.

Vision and Potential Transformative Impact

Our Ocean-Shot vision is a series of scalable TZ observation networks emplaced in critical locations throughout the global ocean, beginning with a pilot observation network off the continental shelf of southern New England. Our team will deploy modular optical, acoustic, and geochemical sensor packages on apex predators, swarms of robots and "smart" floats, and tow bodies deployed from oceanographic vessels and other vessels of opportunity. Network sensors will log biophysical measurements at sub-Hz frequencies across 250,000 square kilometers over several years. In-water assets will connect to autonomous surface vehicles to facilitate data acquisition and assimilation in real time complemented by miniaturized multiple-frequency acoustic receivers that detect sound emitted by sources deployed on an array of moorings for tracking assets throughout the water column. Data from sensor packages deployed on apex predators will lead us to "hotspots" of activity and inform locations for intensive field operations using conventional shipboard technologies. The network will stimulate rich opportunities for advancement of scientific equipment, engineering, and data analysis that will drive new knowledge. The resulting data will transform efforts to inform policy and implement strategies for conservation and sustainable fisheries management in the high seas, as well as predicting the impacts of climate change.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Woods Hole Oceanographic Institution (WHOI) is well positioned to lead the development of an international TZ observation network. The WHOI community of scientific and technical staff, ships' crew and officers, and support staff facilitates several large projects funded by public and private sources with relevance to our Ocean-Shot. We have started Year 3 of a six-year, $32m OTZ Project funded by philanthropic sources. The Northeast U.S. Shelf (NES) Long-Term Ecological Research (LTER) project, funded by NSF, is also based at WHOI. The LTER integrates observations, experiments, and models to understand how planktonic food webs are changing in shelf ecosystems adjacent to the proposed OTZ Observation Network. Finally, WHOI is lead organization for the Ocean Observing Initiative's Pioneer Array that is also located on the NES. We will leverage the knowledge gained, technologies under development, and engineering and technical capabilities from these efforts to ensure that our vision is realizable.

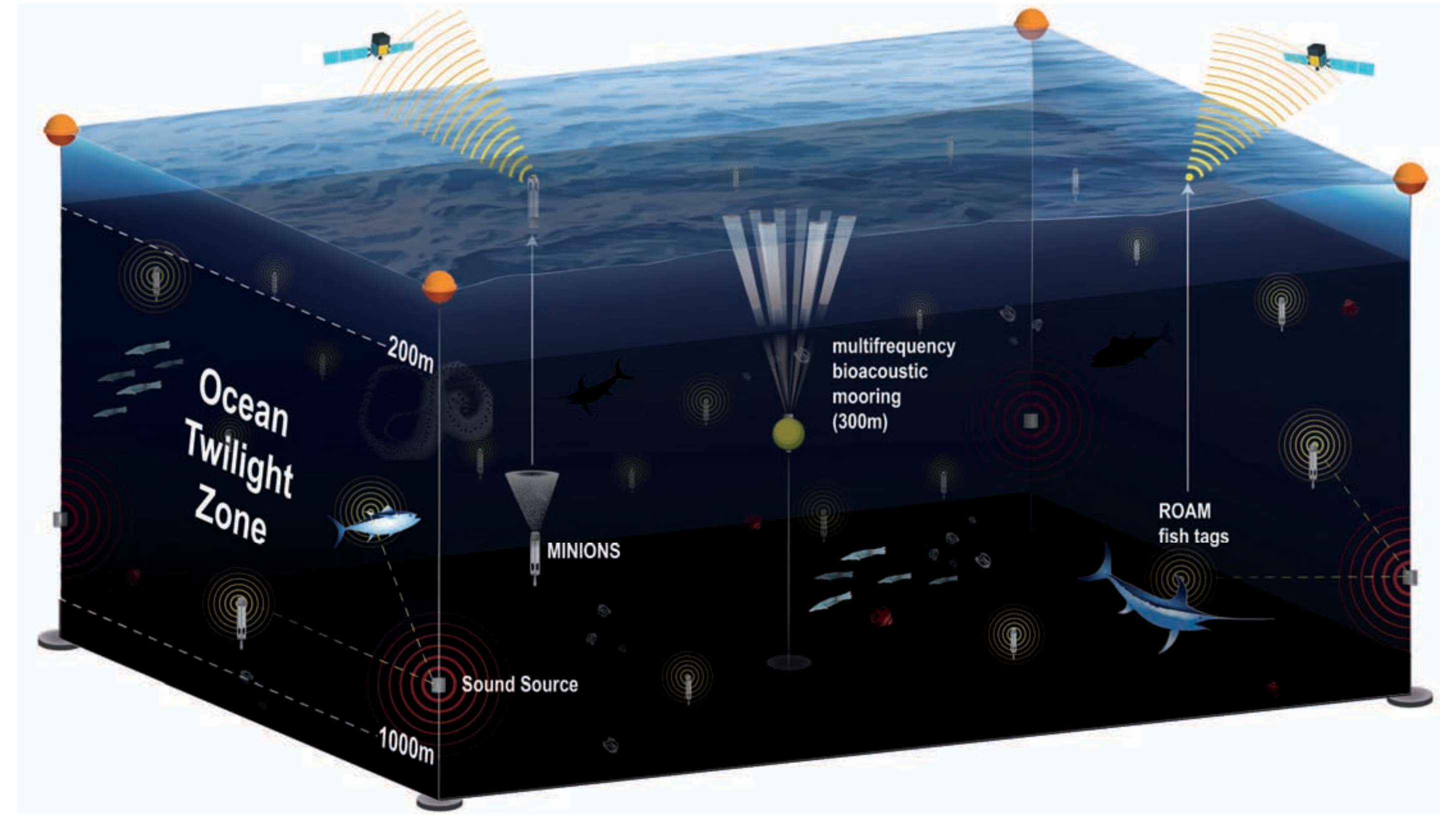

Figure 1. Artistic representation of the Twilight Zone Observation Network that will allow biological and autonomous assets to be tracked throughout the water column in the open ocean. Assets will communicate with each other and data from new smart sensors will be delivered to researchers in near-real time through satellite telemetry.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Our TZ observation network aligns with the Defense Advanced Research Projects Agency's (DARPA) Ocean of Things (OoT) initiative that aims to "enable persistent maritime situational awareness over large ocean areas by deploying thousands of low-cost, environmentally friendly, intelligent floats that drift as a distributed sensor network." Their goal is to establish real-time communications with swarms of floating and swimming sensors. The sensors will use common technologies including GPS sensors, accelerometers, microphones, temperature sensors, and cameras. Several private companies are also invested in OoT. There are natural synergies between our Ocean-Shot and OoT that will be formalized during program development.

Opportunities for International Participation and Collaboration

International scientific interest in the mesopelagic zone is expanding rapidly. For instance, in the past year an informal organization called the Joint Exploration of the Twilight Zone Operational Network (JETZON) has been established to serve as an international coordinator and focal point for mesopelagic studies. This Ocean-Shot would invite members of the JETZON group that aims to bring together all researchers in the field, from PhD students to those involved in, and leading large multinational projects. This OTZ Observation Network will serve as a testbed for the development of similar arrays distributed across TZs throughout the global ocean.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

We often speak of the "democratization" of data, enabling scientists from around the globe to access raw data to advance their own scientific interests. This OTZ observation network aims to set a new standard as one of the tenets of our current OTZ project is open sharing of data. This project will also advance the vision of the OTZ project to reduce "barriers to entry" for ocean science institutions in the developing world by developing low-cost pervasive sensors. We are hopeful that this democratization will also help to inspire prospective ocean scientists from these nations to seek further education opportunities.

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Sustained Open Access Global Wave Observations for Science and Society

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ABSTRACT

Studies of the generation and propagation of surface waves in the open ocean have been traditionally supported by sparse observations. Wave climatology is only known through data from expensive and heavy open ocean moorings, often not optimized for observing surface waves, coastal wave observing networks, or from satellites that can only measure the wave's amplitude. Yet, knowledge of wave physics is of fundamental importance to understand how the ocean and the atmosphere are coupled and to quantify, for example, exchanges of gas and momentum. Of similar importance is understanding how oceanic mesoscale, such as eddies and boundary currents, affect wave steepness and propagation; ultimately important to quantify, for example, hazards to navigation and to protect coastal communities from floods. Scientific advances in data assimilation and wave resolving models, which are supported by our visionary approach, are needed to improve coupled models to support extreme events modeling and forecasting and for improving climate assessment. In-situ global wave observations are one of the obviously missing key ingredients that are hampering progress in oceanography, meteorology, and climate sciences.

Vision and Potential Transformative Impact

Global sustained direct observations of surface waves of scientific quality are not existent. This incredible lack of knowledge negatively impacts a broad range of activities and services such as climate and ocean physics research, maritime transportation, coastal inundation warnings, hurricane intensification forecasting, transport and mixing of pollutants and marine debris, to name a few. Technological advances in the past two decades now support high-quality surface wave observations, including their amplitude and directional properties. Existing ocean observing programs that have demonstrated their sustainability for decades revolve around well focused research-related foundations and can be quickly expanded in scope to entertain the addition of new sensors of critical direct importance for society, and for indirect benefits to society through improved scientific representation of the ocean surface and of forecasting services. Our vision is that of deploying a sustainable and environmentally friendly array of open-ocean, freely drifting expendable wave drifters that provides freely accessible data of sea-state that are scientifically accepted through a rigorous peer-review process and are seamlessly deployed through existing ocean observing infrastructures that have proved their sustainability and scientific impacts.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Wave sensors for amplitude and direction over the range of frequencies of interest for ocean applications based on GPS technology were developed in the late 1990s. Several scientific programs, like the NOAA-funded Global Drifter Program (GDP, Centurioni et al., 2017b) of the Scripps Institution of Oceanography have developed wave drifters that fit with the program's goals of scientific integrity based on peer-review, open data access, sustainability, global coverage, international collaboration and partnership with the private sector (Centurioni et al. 2019, 2017a).

The GDP is committed to minimizing the environmental impact of expendable instruments. As such, drifter solutions using biodegradable/non-toxic materials are being introduced into operations. The envisioned global wave array will benefit from the existing GDP infrastructure that includes well-organized logistics, real-time public data relay, technical expertise, international coordination within the World Meteorological Organization, and will expand the capabilities of the private sector and other partners already collaborating, or wishing to collaborate, with the GDP and that are willing meet the principles of findability, accessibility, interoperability, reusability, and to adopt an explicit data-capable open license (FAIR/O).

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

We envision that the wave data from the open-access GDP wave drifter array will benefit all ocean and climate scientists and will provide an observing baseline of unprecedented quality to scientists and engineers concerned with the design of off-shore structures that include floating platforms such as oil rigs, wave and wind energy farms, as well as ship engineers. It will also assist government and private entities concerned with risk assessment evaluations that need, for example, to evaluate the exposure of coastal communities to inundations cause by extreme events in a changing climate scenario.

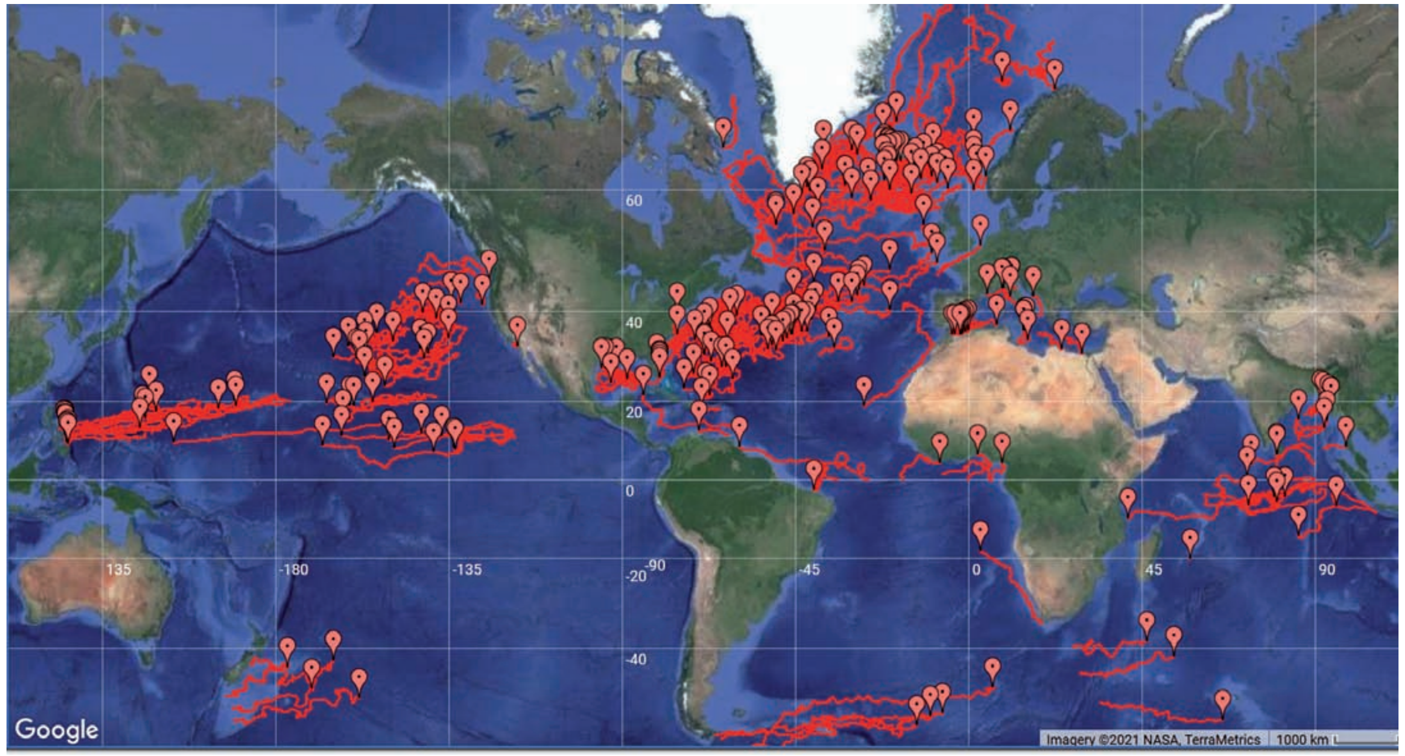

FIGURE 1. Directional Wave Spectra Drifter (DWSDTM) global pilot array as of May 4, 2021.

Opportunities for International Participation and Collaboration

International collaboration is already part of the GDP mission. In fact the GDP could not exist in its present form without the collaboration between countries, regulated within the Data Buoy Cooperation Panel, that contribute with data analysis and deployment of drifters, real-time data relay and quality control, drifter hardware, and technical development. We envision that the existing collaborative framework will support the proposed wave array, and will facilitate the use of our observations by many meteorological agencies and hydrographic offices around the world that already use the GDP drifter data.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers and Technologists

Our open data policy will empower all countries around the globe and as such it will encourage open participation of the private and public sectors globally, as it is already the case with the traditional GDP drifters (Centurioni, 2018) that measure sea-surface temperature, near-surface ocean currents, and atmospheric pressure. The GDP is run from the Scripps Institution of Oceanography, an academic institution, and will continue, together with its national and international partners, to promote the use of drifter data, including the new wave observations, to train the next generation of ocean and climate scientists. Note that over 1,200 peer-reviewed publications using traditional drifter already data exist.

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Marine Health Hubs: Building Interdisciplinary Regional Hubs of Excellence to Research and Address the Societal Impacts of Marine Debris

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ABSTRACT

The marine debris challenge requires an interdisciplinary solution, integrating environmental management, public health, stakeholder engagement, capacity building, along with scientific advances. Marine Health Hubs (MHHs), or regional hubs of excellence utilizing interdisciplinary collaboration to tackle marine debris from environmental, economic, and social perspectives, including health and social equity, are a proposed solution to address this challenge. Applying a collective impact approach, MHHs would build capacity across the research-to-application continuum: advancing research and technology development, translating science for informed policymaking, increasing awareness through outreach and citizen engagement, and establishing performance-based programs for accountability and continuous improvement. Across this continuum, stakeholder engagement would ensure locally and culturally appropriate research, tools, and interventions. The strategy and prioritization of each MHH's activities would vary, depending on a region's infrastructure, assets, and needs; however, utilizing a capacity-building framework, MHHs would implement consensus-based agenda setting, and applied learning for knowledge transfer and peer-to-peer information sharing. This framework has been successfully employed for other environmental governance efforts seeking to address transboundary environmental health threats. Through co-development, co-design, and co-investment, MHHs would serve as self-sustaining programs capable of adapting to evolving needs, efficiently utilizing resources to reduce plastics pollution, and improve environmental and health outcomes.

Vision and Potential Transformative Impact

The Marine Health Hubs (MHHs) program would draw upon the UN's three pillars of sustainable development—economic, social, and environmental—to comprehensively address the global challenge of marine debris. The vision of the program would be carried out via MHHs or self-sustaining regional hubs of excellence that will utilize interdisciplinary collaboration to tackle the burden of plastic marine waste, not only from an environmental and economic lens, but also through a social lens to better understand the critical knowledge gap in potential impacts on human health and other social equity concerns. Leveraging U.S. and global subject matter expertise and best practices in environmental and marine science, public health, chemistry, social sciences and other relevant fields, coupled with technological advances and techniques for analysis, prevention, capture, and removal of plastics, MHHs would build capacity for and mobilize interdisciplinary teams worldwide to address marine debris across the continuum of research to application. By building global capacity around advancing research and technology development, improving data collection and management, translating science for informed decision- and policy-making across various scales and sectors, increasing awareness through public outreach and citizen engagement, and establishing performance-based programs for accountability and continuous improvement, regional teams could identify and prioritize actionable solutions to addressing plastics pollution for improved collective impact worldwide. In addition to better understanding and addressing existing marine debris impacts, MHHs would also work to mitigate future marine debris impacts through innovative technology development of sustainable alternatives or the promotion of circular economies to prevent plastic pollution.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Recognizing the vast landscape of ongoing marine debris efforts, the program would leverage existing disparate efforts across public and private sectors with the aim of improving coordination and sharing of expertise, lessons learned, best practices, and innovative approaches across countries and regions working to tackle this issue. Across the U.S. government, existing efforts and networks, such as NOAA's Marine Debris and SeaGrant programs, EPA's marine litter and Trash Free Waters programs, and NIEHS's Oceans and Human Health program, offer access to vital resources such as infrastructure, data, and stakeholder relationships, both domestically and internationally. The program would connect existing programs with the broader public health research community (e.g., EPA, ATSDR, NIEHS, CDC). Beyond the United States, the program would leverage established leaders and networks of existing UN efforts (e.g., Global Partnership on Marine Litter, Clean Seas, Coordinating Body on the Seas of East Asia [COBSEA]). Additionally, the program would engage academia and the private sector to leverage research expertise across physical and social sciences, public health, economics, and promote innovative and breakthrough technologies to address this challenge.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

The MHH program would balance scientific and technological advances along with the promotion of sustainable development goals and social equity across environmental, economic, and social perspectives. Therefore, engagement across both physical and social sciences is required, coupled with broader engagement with sectors such as public health to better understand direct and indirect threats to human health from macro-, micro-, and nano-plastic pollution, as well as waste management and materials engineering to rethink the way we design, use, and reuse plastics to promote a circular economy to reduce waste. Establishing capacity and credibility for in-country research and technology development, and connecting researchers to policy- and decision-makers would result in improved governance and evidence-based interventions, such as comprehensive, interdisciplinary debris management strategies and action plans to maintain our oceans for future generations.

Opportunities for International Participation and Collaboration

The development of self-sustaining regional hubs of excellence across the world requires active engagement and leadership from international cohorts. The applied learning approach would engage subject matter experts from across the globe, particularly from regions already demonstrating leadership on this issue (e.g., Southeast Asia) to transfer knowledge. Once established, MHHs would promote peer-to-peer information sharing and work with stakeholders, particularly in lower- and middle-income countries, to co-develop realistic and actionable marine debris management plans that will not only address ecological, health, and economic concerns, but also promote sustainable environmental and public health governance and social equity.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The program would leverage the use of academic institutions and faculty, as well as other key stakeholders across public and private sectors, to deliver formalized undergraduate and graduate coursework, as well as continuing education credits for various professionals participating in relevant professional development activities. Additionally, opportunities for post-doc and early-career fellowship opportunities focused on sub-themes of interest would also be explored through public–private partnerships. Furthermore, the program could also utilize citizen science and STEM education to reach primary and secondary education students, increasing awareness of and exposing students to potential career opportunities related to preserving our oceans from marine debris.

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Building Ocean Collaborations

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ABSTRACT

Communicating the value of sustained ocean observing systems is urgent and necessary for their implementation, continuity, and expansion; and relies on effective dialogue among users at all levels to build support from policymakers and the public.
This Ocean-Shot will build on the outcomes of OceanObs'19 and specifically work to realize the vision articulated in "The Challenge of Sustaining Ocean Observations" (Weller, 2019) and subsequent workshops hosted by the National Academies (2020). It will engage academia, industry, government, and nongovernmental organizations involved with global ocean observing and determine how to improve pathways to policymakers, stakeholders, and the public over the UN Ocean Decade. Key outcomes will include (1) broader understanding of how existing ocean observing science and policy areas intersect nationally and internationally, (2) identification of opportunities to build global support for ocean observing through cross-sector and international partnerships, and (3) determination of actions that the ocean observing community should take to develop a collective impact organization, the Ocean Partnership for Sustained Observations.

Vision and Potential Transformative Impact

Ultimately, building ocean collaborations will result in the development of a shared measurement system that promotes a common agenda with agreement on how success will be measured. The transformative impact is the ability to improve quality and credibility of ocean data as well as to document progress on critical ocean programs. This will include 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 (Weller, 2019).

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

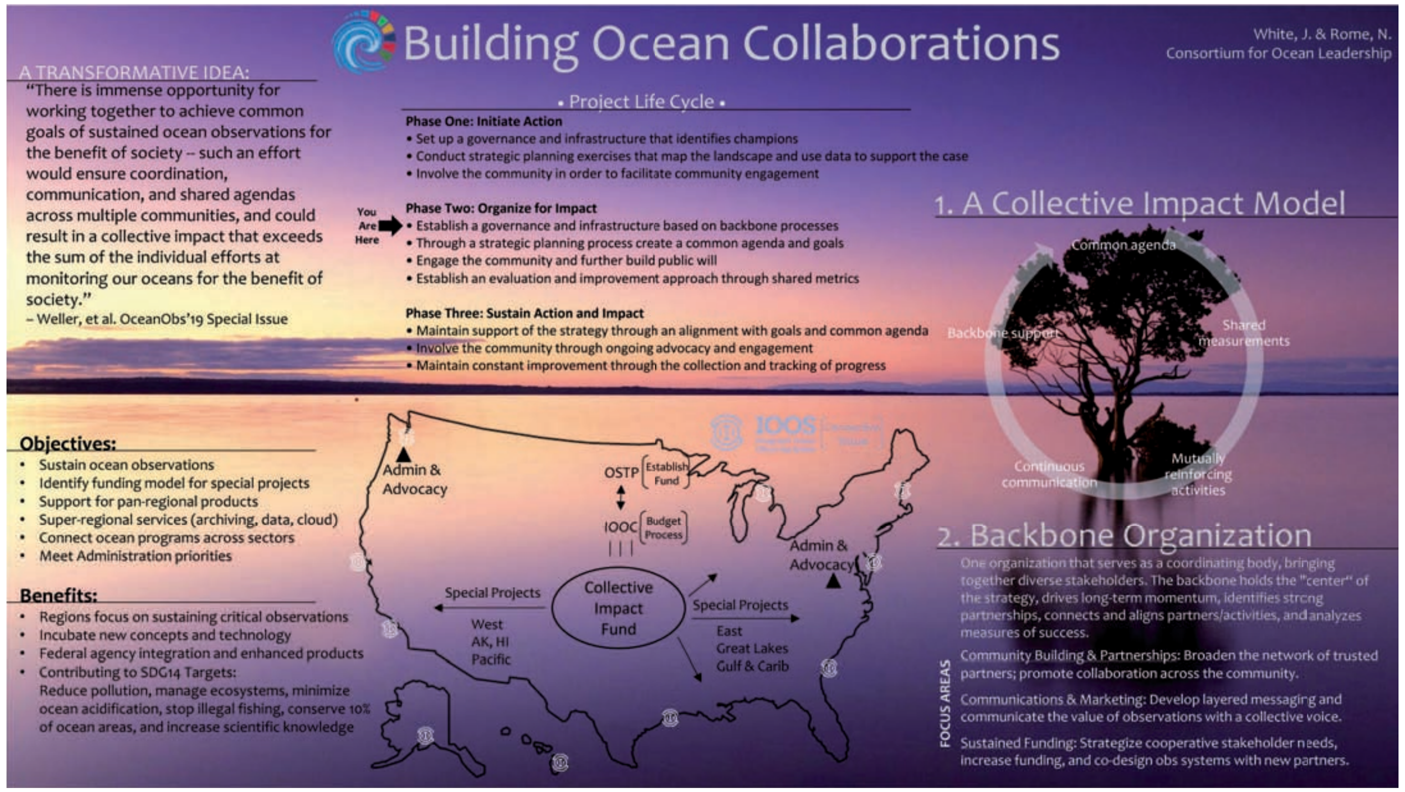
The goal is to promote collaborations across U.S. actors from all sectors with scientific technology and infrastructure. Realistic connections would occur on appropriate polycentric levels, as articulated in a Collective Impact Organization model. U.S. stakeholders and funding agencies will promote early and consistent connections and dialogue amongst researchers, engineers, technologists, and data science communities at the inception of observing programs to ensure that objectives and requirements are met. Distributed and extensive ocean observing platforms, infrastructure, and systems are required to increase community emphasis on turning prototype tools and individual sensors into integrated platforms and production systems using best practices in systems engineering and data management. Finally, the ocean observing community will establish a stronger pipeline for innovators from engineering, computer science, data science, and material science.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

An overarching goal is to identify willing champions and experts to facilitate a network of advisors and collective impact organizations that help with trans-sector partnership development and maintenance at national to regional to global scales. Nontraditional actors—e.g., marketing and organizational experts—are needed to design and implement a structure for the development and resourcing of global partnerships around capacity building and maintenance in ocean observations (and larger ocean science). Nontraditional stakeholders—e.g., insurance and agricultural representatives—are also essential for creating a framework for partnership building that provides guidance for research institutions, countries, philanthropies, etc. that wish to establish programs around ocean observations, products, and services.

Opportunities for International Participation and Collaboration

The United States would take a leadership position in initiating this effort and apply successful collaboration models worldwide. Capacity building across the entire observing community is required to ensure international momentum of the oceans in a more holistic and integrated way, considering the oceans as a socio-ecological system, including the engagement of students and early career individuals to strengthen the future workforce. This also includes increasing the capacity of developing countries to produce continued observations that are fit-for-purpose of their policy concerns but, at the same time, useful to inform at the global level.



Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Building ocean collaborations is open and transparent, engaging the institutional knowledge and engaging future leaders in ocean science. The effort will create venues and opportunities for dialogue about capacity development between scientists, high-level decision makers, local implementors, and other stakeholders. Ultimately, it's about aligning efforts with community needs and realities to ensure training matches available equipment; create regionally specific best practices, including for import/procurement of equipment; and guarantee easy and sustainable maintenance. The collective impact organization will create a community of practice to share resources, catalogue existing efforts, create a unified agenda, obtain funding, and ensure sustainability of efforts.

The first stage for sustaining long-term support for ocean observing is establishing the backbone organization that can provide marketing and organizational capabilities, one option being a "National Ocean Observing Foundation" using the National Fish and Wildlife Foundation as a model. Such an organization may require about $10 million. A key activity of this organization would be to bring in new partners. Having a good story and being well organized will be necessary for the second stage: an established endowment for a sustained, global ocean observing system on the order of $10 billion endowed to operate at a cost of $1 billion annually.

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Ocean Technology Field Academy—Empowering Ocean Stakeholders for a Sustainable Future

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ABSTRACT

Data generated from ocean observing, or ocean-atmosphere coupled observing, permeates every facet of ocean research, ocean sustainability efforts, and the blue economy and offers workforce opportunities for all education levels. The Decade of Ocean Science for Sustainable Development and the Seabed 2030 effort will capitalize on the data availability and place a spotlight on the increased need for a workforce capable of analyzing and applying these data to generate solutions for sustainable ocean uses.

Although most jobs will not require advanced degrees in engineering or science, the preparation of the 21st century ocean technology workforce demands an understanding of marine science and other disciplines, an ability to resolve complex environmental issues, and the ability to communicate complex ideas to a broad audience. Fostering these critical abilities will require a new set of learning opportunities. Developing and maintaining such a workforce will rely on innovative and flexible educational programs that break through the traditional "siloed" approach to education, while offering multiple and rapid pathways for degree and certification attainment.

In response, we propose a program to prepare a workforce with the ability to utilize sensors, sensor platforms, sensor networks, crewed and uncrewed surface/underwater vehicles, sonar systems, and data processing capabilities.

Vision and Potential Transformative Impact

The purpose of this proposal is not to generate an entire new curriculum, but to pivot and modify existing curricula and create certification pathways to address the growing workforce needs. Students will emerge from the program with a multi-faceted perspective as a scientist-engineer-technician (SET). However, the transferability of these skills and competencies will be reinforced to ensure connections to other applications or careers (i.e., transferable electrical skills). The program will emphasize opportunities for authentic, hands-on learning and collaborative teamwork, and will provide engaging and practical experience in systems thinking with marine-themed activities.

FIGURE 1. NMC-MTS Marine Technology Summer Camp 2016.

The project will stimulate awareness of and interest in STEM careers by:

- accessing and utilizing an unprecedented quantity of environmental data;
- exposure to relevance in today's R&D environment;
- preparing to directly transition into other career opportunities;
- providing a credentialing mechanism to accelerate their education;
- preparing to directly transition into a variety of college, university or technical programs.

Growing from a proof of concept program with existing partners in Indonesia, additional partners and sites will be created with a focus on supporting Least Developed Countries (LDCs) and Small Island Developing States (SIDS) and sharing educational materials with the Ocean Teacher Global Academy.

FIGURE 2. Study abroad students participating in sonar training program.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

A collaboration between Northwestern Michigan College, Eidos Education, industrial partners (Fugro, R2 Sonic, QPS, Kongsberg), and professional societies will address these needs for technician preparation by developing a micro-credentialing schema for college (equivalent) students. The "core" credentials will reflect mastery of fundamental science, technology, engineering and mathematics (STEM) principles through the lens of marine science, fisheries science, and applications of technologies essential for Blue Economy operations and environmental research, while creating pathways for expeditious entry into the workforce. The industry partnerships will ensure students will receive state-of-the-art credentials of value and enable long-term equipment needs in partner locations to facilitate hands-on training. We will also work with the local partners to determine the most appropriate local applications of the technologies for the students to study on a long-term basis.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

This project will not seek the development of new technologies or scientific discovery, rather focus on democratizing access to and application of existing ocean exploration technologies including ROV, UAS, scanning sonar, ADCP, Lidar, and use of supporting software in critical regions around the globe. While these tools are used by Tier 1 programs in the United States, many of these tools are still not available to smaller schools and programs in the United States and other countries. This program will provide hands-on access to the tools to create a local workforce prepared to address local issues and assisting research scientists.

Opportunities for International Participation and Collaboration

A proof of concept program will be created by leveraging an existing partnership with Manado State Polytechnic and the Bunaken National Park, located in North Sulawesi, Indonesia. The proof of concept will build local capacity for the application of unmanned systems and technologies to continually monitor and work to improve their coral reef system, one of the most biodiverse populations of corals in the world. As a local application of the program training goals, students will conduct surveys to map bathymetry, habitat, coral type and locations. Additional locations will focus on applications of local interest in consultation with the local partners.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The program will create a "train the trainer" model and create partnerships with local colleges or universities to establish a node of local "trainers" and serve as points of contact for equipment deployments. The "train the trainer" model will include three rounds of training: 1st) Introduce and educate; 2nd) Development of competency; and 3rd) Demonstrate competency and local training regime. Materials will be available through the program website and through the IOC's OceanTeacher Global Academy to expand the network of schools offering the program. In addition, program recruitment/informational materials will be disseminated in conjunction with Ocean Literacy efforts.

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An Ocean Science Education Network for the Decade

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ABSTRACT

Ocean science education and ocean literacy are overarching components of all Ocean Decade challenges. Educating the next generation of ocean scientists will help achieve Ocean Decade objectives, while increasing public ocean literacy will motivate citizens to engage in the ocean science enterprise. During the UN Ocean Decade, a coordinated flow of information among scientists, educators, policy makers, business leaders, and the public will help guide research priorities in addition to enhancing citizens' ocean literacy. Ocean literacy is about more than the acquisition of ocean science knowledge. It also relates to critical needs for citizens to become responsible in sustainably using the ocean and its resources. Society must gain scientific understanding of the ocean's responses to pressures and make management decisions that are fundamental for sustainable development of its resources. U.S. ocean science education, outreach, and communication initiatives have been greatly expanded since 2002 due to the work of the National Science Foundation-funded, national Centers for Ocean Sciences Education Excellence (COSEE; now the Consortium for Ocean Science Exploration and Engagement) network. The infrastructure established by COSEE is well-poised to take on the establishment of a network of networks to forge U.S. leadership in robust international collaborations in support of Ocean Decade objectives.

Vision and Potential Transformative Impact

Ocean literacy is necessary for teachers, students, policy/decision makers, business personnel, and the public so that all can make informed decisions within their arenas of influence. Enhanced ocean literacy has the potential to transform actions, leading to more inclusive and equitable decisions and fostering conservation and stewardship-minded behaviors. To grow a globally ocean literate citizenry and workforce, the United States should build on its national COSEE network of ocean science research and education institutions. From 2015–2019, COSEE, in collaboration with the College of Exploration and Intergovernmental Oceanographic Commission (IOC), has conducted the *Global Ocean Science Education (GOSE) Workshops*. These cross-sector events have provided opportunities for ocean scientists, education professionals, policymakers, and business leaders to identify ocean education priorities. The November 2019 GOSE Workshop identified a critical priority for the Ocean Decade—the establishment of a network of networks engaged in ocean science education, across K–graduate level and informal science education. The United States should take a leadership role in developing this network, as the professional infrastructure already exists through COSEE and the GOSE community. Such a network would have a transformative impact through collaborative activities that reach citizens across the United States and the globe, using effective practices.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

An Ocean Science Education Network for the Decade would build on existing regional, national, and international networks to reach all segments of society. Key Network goals would be to: (1) Encourage cooperation and best practice exchanges related to ocean science education, resulting in improved global ocean literacy; (2) Raise awareness of interactions between the ocean and peoples' daily lives, and empower citizens to adjust everyday behavior; (3) Assist the ocean science enterprise in improving diversity, equity, and inclusion, including across Indigenous populations; (4) Establish pathways to grow and educate the blue economy workforce; (5) Seek and apply innovative ways to make current and future generations ocean literate so that they can make informed decisions related to ocean stewardship and use of ocean resources that ultimately translate into ocean policy; and (6) Engage citizens and communities in ocean research. These goals will be attained through leveraging existing resources and infrastructure and establishing new partnerships.

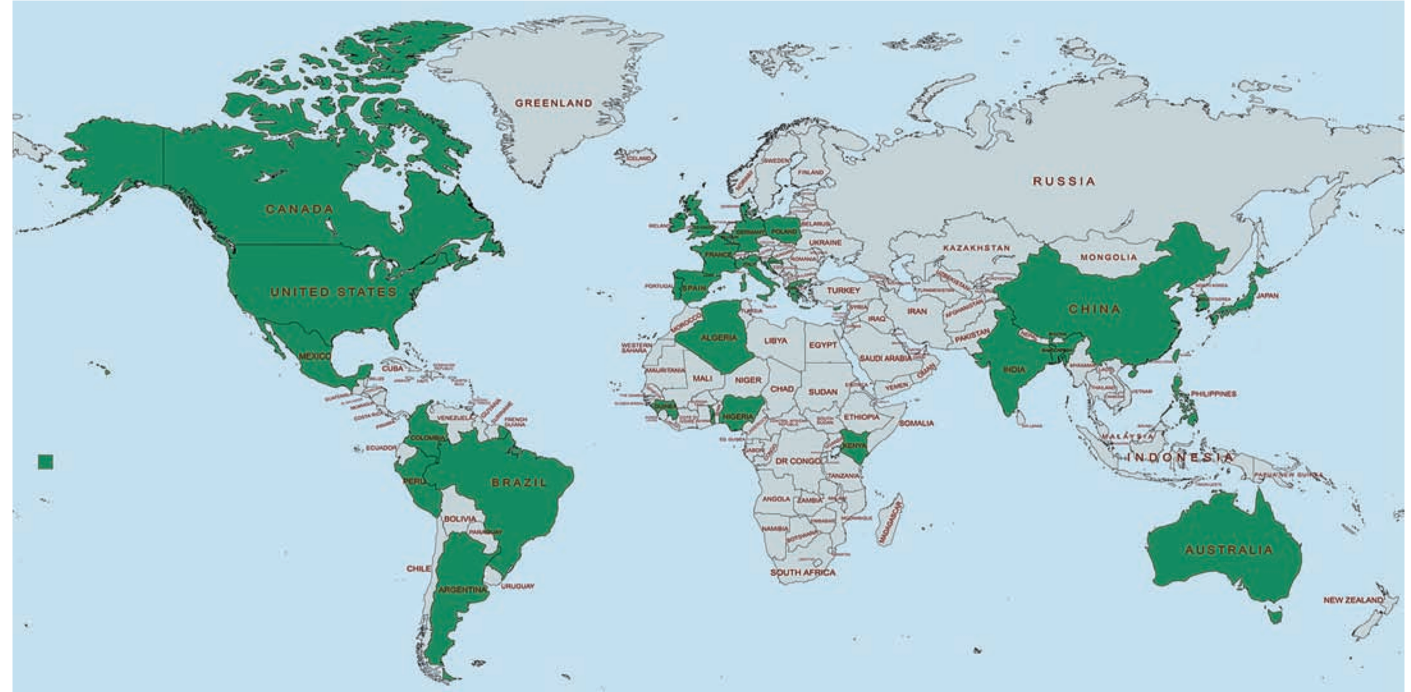

FIGURE 1. Countries represented by delegates to the GOSE Workshops.

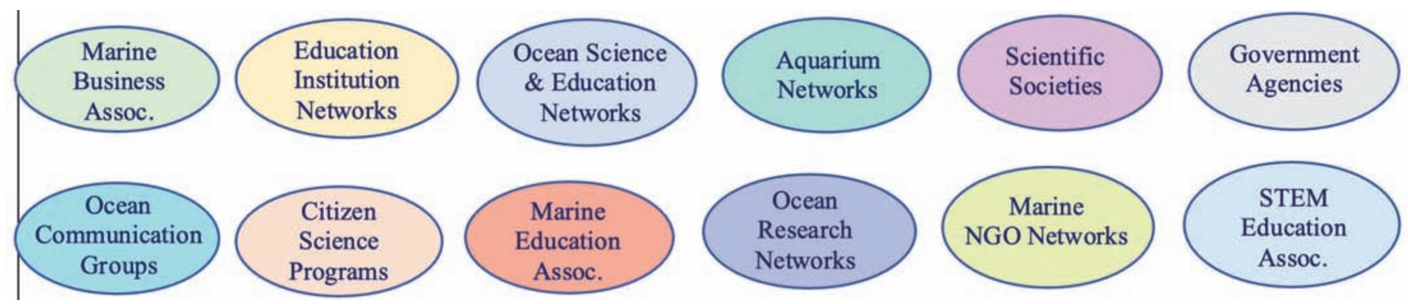

FIGURE 2. Examples of networks and associations to be represented in the Ocean Science Education Network for the Decade.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

An Ocean Science Education Network for the Ocean Decade would include international working groups comprised of multi-sector representatives to:

(1) Develop common ocean science messages and communication tools;
(2) Promote workforce development to meet needs of the growing blue economy;
(3) Contribute to the IOC ocean literacy platform for sharing information about resources, projects, and people;
(4) Establish citizen engagement opportunities related to Ocean Decade objectives;
(5) Develop resources for the policymaker/decision maker community; and
(6) Establish international collaborations to promote ocean science research.

Opportunities for International Participation and Collaboration

The GOSE Workshops have been effective forums for ocean scientists, education professionals, policymakers, and business leaders to participate in cross-sector discussions related to ocean science education and ocean literacy. These interactions have served as catalysts to develop the first international training program for business leaders, identify growing blue economy workforce needs, and identify priorities for global ocean literacy. The establishment of an Ocean Science Education Network for the Ocean Decade would allow for an expansion of international participation and collaboration to include representatives from Indigenous communities, Small Island States, and other groups who are underrepresented in ocean sciences.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Through a coordinated network of networks, there is great potential during the Ocean Decade to grow a blue economy that sustainably uses the ocean and its resources by recruiting and preparing the necessary workforce, including the next generation of ocean scientists. This will need to be a collaborative workforce, capable of resolving complex issues with a trans-disciplinary understanding of the ocean and an ability to integrate science concepts, engineering methods, business acumen, and sociopolitical considerations. By facilitating cross sector interactions, the Ocean Science Education Network for the Ocean Decade can foster the partnerships and collaborations needed to fill the ocean science pipeline.

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Sustaining Ocean Observations: Strategic Messaging and Communications

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ABSTRACT

Arguably the most important outcome of the Sustaining Ocean Observations 2.0 Workshop hosted by the Ocean Studies Board was "Strengthening the Collective Voice: Communicating the Importance of Sustained Ocean Observations." One of the most significant challenges the ocean observing community faces is articulating the value of ocean information and improving ocean literacy.
The Ocean Decade presents a pivotal moment to catalyze new effort and funding that will support strategic and unified messages regarding the role that observations play in society. Led by the Consortium for Ocean Leadership (COL), the proposed strategic messaging and communications initiative will develop consistent, layered, and clear messaging regarding the value of ocean observations. COL will leverage existing interagency programs and trusted partners, along with external academic, policy, and industry collaborators, to obtain funding and other resources to support the initiative. This Ocean-Shot will build on ideas put forth by Ocean Obs'19, the Ocean Best Practices System, and other UN Ocean Decade initiatives. Primary activities will include hiring communications experts, surveying the community and relevant partners to collect input on the role of observations, and identifying messaging gaps. This effort would strengthen the community's collective voice to demonstrate the value of observations to potential funders, philanthropic or private partners, and governments, and would address the needs of the technology sector.

Vision and Potential Transformative Impact

The marketing and communications initiative would transform the ocean sciences community by developing clear and consistent messaging for dissemination throughout the ocean observing community and all stakeholders in observations. Currently, communications outside and within the community are disconnected and do little to engage with all funders, stakeholders, end-users, and those who rely on the ocean.

To address these problem areas and communication gaps, the initiative's comprehensive strategy will promote sustainable observing systems by providing the community with a well-defined and consistent message, eliminating any confusion and strengthening their voice. By achieving enhanced communications, this would also highlight the value chain of observations and promote engagement with private industry groups to help them better understand how observations impact their community, creating new avenues for obtaining resources and funding.

Furthermore, this initiative would strengthen existing observing networks by promoting collaborations. COL will encourage organizations throughout the observing community to partner and agree on layered messaging that would improve ocean literacy and build on the UN Ocean Decade. If found to be effective, further marketing and communications materials could continue to be deployed for specific needs, such as those of the technology sector.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The communications and marketing initiative will leverage networks already existing within the observing community, such as the Interagency Ocean Observing Committee (IOOC), the Integrated Ocean Observing System (IOOS) Association, National Oceanographic Partnership Program (NOPP), and others. These networks will allow the taskforce to obtain a comprehensive understanding of the community's current messaging needs and gaps that may exist within ocean observing communications. With information obtained from the community, comprehensive, layered messaging will be developed. Public–private partnerships will be key and connections to these diverse networks and partnerships existing within the United States will allow development of clear and concise messaging and support the broad observing community. While aiming to build and strengthen existing networks, the initiative will also foster new partnerships with public and private entities, as well as philanthropic and government bodies. It is also anticipated that bolstering communications through this initiative would lead to more funding for more technology in the future.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Telling a persuasive story about the importance of ocean observations and technology to society requires engagement from nontraditional scientific fields. Effective messaging and communication will depend on collaboration with social scientists, who can provide input on stakeholder needs and techniques for forming new relationships. Technology is rapidly advancing our ability to understand the ocean and generating volumes of new data. The broad range of uses and opportunities will be marketed to engineers, data scientists, and even coders to illuminate potential places for collaboration.

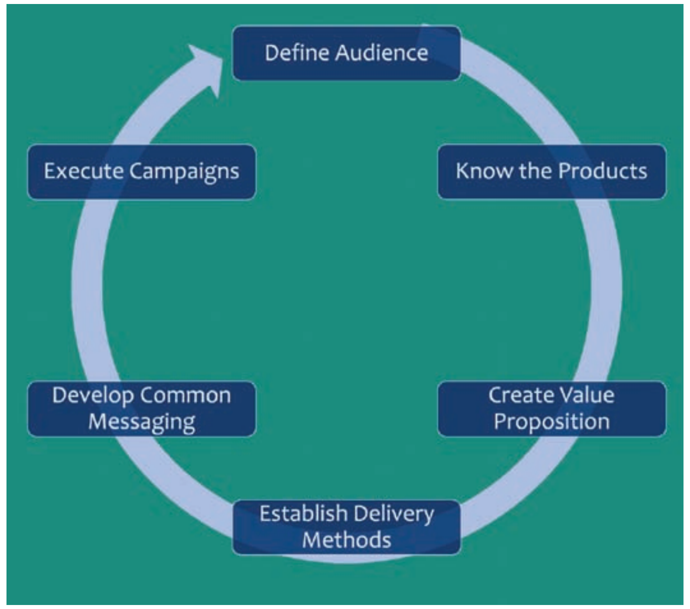

FIGURE 1: Proposed approach for a strategic communications and marketing process.

Opportunities for International Participation and Collaboration

The communications and marketing initiative will engage with the international community to collect data and case studies on how observations have changed science, technology, and society in diverse ways around the world. For example, the connections and activities spurred by the international OceanObs'19 conference, which involved over 1,500 participants from 74 countries, can be leveraged. This global network of scientists, managers, and end-users represents the wide range of observation applications and undoubtedly holds compelling stories that will be mined to create a more comprehensive picture of ocean observing, including key contributions of international governance bodies and Indigenous and underrepresented groups.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Ocean observations encompass a wide variety of scientific fields, including physical, biological, and chemical observations. Observations are rapidly advancing with technological innovation, and offer opportunities for scientists with a variety of backgrounds and concentrations to play a role. A clear and persuasive message about the broad value of observations to society will attract more young scientists to study the oceans and ocean observations. Strategies will include engagement of students and scientists via social media and other media that connect with the next generation, ultimately strengthening the ocean STEM pipeline.

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EquiSea: The Ocean Science Fund for All

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ABSTRACT

Ocean science capacity is distributed unequally, but a rapidly changing ocean requires widely and equitably distributed human, technical, and physical ocean science infrastructure. EquiSea: The Ocean Science Fund for All is a platform co-designed through consensus-based stakeholder discussion with more than 200 scientists from around the world. EquiSea aims to improve equity in ocean science by establishing a philanthropic fund to provide direct financial support to projects, coordinating capacity development activities, fostering collaboration and co-financing of ocean science between academia, government, NGOs, and private sector actors, and supporting the development of low-cost and easy-to-maintain ocean science technologies.

Vision and Potential Transformative Impact

Sustained ocean science requires a strong supporting environment, including consistent national government allocation of funding for ocean science, well-maintained research facilities and offshore assets, and a healthy job market for ocean science professionals. Robust ocean science capacity can thus be defined as having the infrastructure and human and financial resources required to predict and respond to dynamic environmental change. Currently, many regions lack the infrastructure, training, and foundational government and funding structures required to sustain ocean observing. EquiSea aims to ensure equitable distribution of ocean science capacity, in particular throughout the UN Decade of Ocean Science for Sustainable Development. To achieve this, EquiSea will:

1. Establish a philanthropic fund to enable equitable distribution of ocean science capacity, including through funding of training programs and infrastructure grants.
2. Coordinate with key international processes and partners to ensure effective delivery of capacity development.
3. Foster collaboration between scientists and policymakers to enhance national support for sustained ocean science programs.
4. Engage private sector actors to provide jobs training and employment opportunities in ocean science.
5. Engage with ocean science technology developers to ensure a pipeline of accessible technology suitable for use in under-resourced regions.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

EquiSea will support collaborations between scientists in the United States and under-resourced nations, thus utilizing one of the key elements of U.S. infrastructure, namely, scientists and the expertise that they bring to their projects. Additionally, EquiSea will support technology development, especially development of lower-cost and other observing technologies that are well-suited to under-resourced and remote regions. EquiSea will also promote public–private partnerships, which can provide jobs for people trained in the ocean sciences in under-resourced nations. For example, the EquiSea will direct co-financing of job placement and training programs with private-sector partners. Large U.S. companies with a marine-sector focus, such as shipping, maritime security, pollution management, and fishing, need to have local employees in all of the countries that they operate in. EquiSea will therefore benefit U.S.-based marine-sector companies by providing them with a trained workforce overseas and potential access to emerging sustainable blue economy markets.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

EquiSea will engage the private sector, the technology sector, and governments in under-resourced regions, which often have weak relations with their scientists. To help build the foundational feedback loop between science, policy, and industry, EquiSea will facilitate discussions between the academic, private, and government sectors, identify projects that bolster a sustainable blue economy, and fund activities that encourage private-sector job creation. To coordinate and focus global efforts EquiSea will also host annual technology workshops that promote appropriate observing technologies for under-resourced regions. Finally, EquiSea will incorporate requirements for government and science connections within proposal calls—for example, projects for new monitoring systems must identify agencies that will be served by the data.

Opportunities for International Participation and Collaboration
Successful implementation of EquiSea will greatly enhance international participation and collaboration. Many under-resourced countries do not have national science funding agencies, and in many higher-resourced countries, funding for international capacity development work is lacking. Consequently, participation of scientists from under-resourced countries in global ocean governance boards, global ocean science meetings, and international journals is sorely lacking, and the number of collaborations between scientists in under-resourced countries and higher-resourced countries is limited. EquiSea will support projects that promote development of ocean science in under-resourced countries, and promote collaborations between scientists in under-resourced and higher-resourced countries.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The focus of EquiSea is to address systemic inequities in ocean science capacity, especially training of the next generation of ocean scientists. EquiSea will support projects that are motivated by these goals. In many countries, there are not nearly enough ocean scientists to take local measurements, train the next generation of scientists, and serve on global ocean governance boards. EquiSea seeks to rectify this major shortcoming in the global oceanographic workforce, through supporting a variety of capacity development projects around the world, especially in underserved regions.

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The Ocean Decade Show: A Podcast to Guide You Down the Yellow Brick Road to Transform the Ocean

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ABSTRACT
To facilitate transformative change around the globe during the UN Decade of Ocean Science for Sustainable Development, we must communicate about the importance of this endeavor and its relevance to the U.S. ocean community and beyond. The Ocean Decade Show podcast aims to be a primary communication tool for Ocean Decade efforts, acting as a monthly source to help individuals learn about the key elements of the Ocean Decade. A podcast is an ideal choice for a communications tool for the Ocean Decade because of its relatable format and emphasis on storytelling; the Ocean Decade is a fantastic, but complicated, story. Our goal with this podcast is to help individuals understand the Ocean Decade story to increase their connection to the overarching effort and its component parts.

Vision and Potential Transformative Impact

The goal of this podcast is to introduce the public to the UN Decade of Ocean Science for Sustainable Development and keep them informed and engaged with international and U.S. domestic activities as they become reality. The Ocean Decade is necessarily a bottom up process—activities at the local, regional, and national level will feed into the success of this global ocean potluck. Using the flexible podcast format, we hope to entice the general public (primarily defined as individuals interested in environmental/ocean issues, but who are not yet aware or directly involved in the Ocean Decade) to tune in and better understand the relevance of this international initiative. The host of The Ocean Decade Show, Taylor Goelz, spent a year as a Knauss Marine Policy Fellow at NOAA Research in the United States; she knows all the relevant players and has the right level of insider knowledge to provide listeners with an insider pass into the course of ocean science over the next 10 years.

We see this podcast as a communication and outreach tool for the Intergovernmental Oceanographic Commission (IOC) and the global community of individuals working on the Ocean Decade. Crucially, the podcast is a way to convey the goals and objectives of the Ocean Decade but in a more approachable, human-centered, story-focused format. The Ocean Decade is being conducted by humans, and telling the human stories of the Decade will help listeners better connect to this initiative.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Coastal News Today, the home of the American Shoreline Podcast Network (ASPN), is a non-profit, non-partisan platform for coastal and ocean leaders, professionals, and concerned citizens to share information and promote discussion. The mission of Coastal News Today is to support the success of shoreline professionals and empower an informed coastal citizenry—illuminating divergent viewpoints among coastal interests and advancing the understanding of new practices, partnerships, and opportunities. ASPN provides cross-cutting content from different coastal industries. Their podcasts aim to gain exclusive insights from across the spectrum of interests to inform better decisions in the U.S. ocean and coasts. ASPN is an established, successful podcast network currently featuring leaders from 11 interconnected shoreline sectors. The Ocean Decade Show is housed within ASPN. Benefits that come from this partnership include tapping into their established network and the ability to connect individuals and bridge disciplines.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

ASPN thrives on providing connections to new and novel sectors, with the aim to bring together stakeholders and help them find similarities. This same approach would be used for The Ocean Decade Show—the format is flexible and the host will have control over setting the course and the direction of podcast topics. This flexibility will allow The Ocean Decade Show to work with National Committees, NGOs, academia, federal, and international partners to feature topics of interest, develop a list of interested sectors to target for outreach, highlight partners, and maintain coordination for Ocean Decade planning and activities.

Opportunities for International Participation and Collaboration

The flexibility of the podcast structure and content has already taken advantage of the opportunity of international participation and collaboration. Individuals from Hawaii to Paris to Stockholm to New York were interviewed for the first three episodes, with continued guests both from within the United States and abroad planned over the course of 2021. The podcast is a communication tool for anyone looking to tell their story of the Decade; by focusing on the human side of this international effort, we can help foster novel partnerships and get greater attention for transformative ideas put forth by the global ocean community.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

According to *PodcastInsights*, 48% of podcast listeners are between the ages of 12 and 34, which suggests that The Ocean Decade Show is a beneficial way to reach the next generation of ocean scientists, engineers, and technologists. Also by focusing on the people behind the science/engineering/tech, we aim to make the Decade more understandable to a broader audience—they get to know the Decade through stories instead of graphs and figures. The benefit of using a podcast to communicate about the Ocean Decade is the ability to translate the high-level policy papers and UN-speak into smaller, comprehensible pieces.

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FantaSEAS Project: Incorporating Inspiring Ocean Science in the Popular Media

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ABSTRACT

One of the goals of the UN Oceans Decade is "an inspiring and engaging ocean where society understands and values the ocean in relation to human well-being and sustainable development." The UN Ocean Decade also calls for promoting diversity in ocean science, engaging multiple stakeholders, including industries and the wider public, as well as promoting ocean science literacy. The FANTASeas project aims to do this.

One major source of inspiration for the general public for millennia has been art and literature. Over the past century, key sources of public inspiration when it comes to science include science fiction and fantasy in books, movies, TV shows, comics and, recently, computer games. Most famously, the TV show Star Trek inspired a generation of space scientists.

The idea behind this project is to promote and facilitate the production of popular artistic and literary projects that incorporate ocean science to enhance both ocean literacy and to create more inspirational ocean-related projects.

It is proposed that a series of international workshops be organized to connect ocean scientists with novelists, writers, and designers from the: (a) computer gaming; (b) tabletop gaming; (c) TV and movie; and (d) comic and graphic novel industries.

Vision and Potential Transformative Impact

One major source of inspiration for the general public for millennia has been art and literature. Over the past century, when it comes to science, key sources of public inspiration have included science fiction and fantasy in books, movies, TV shows, comics, and recently computer games. For example, the books of Isaac Asimov and Robert Heinlein, Star Trek, 2001 a Space Odyssey, and so forth.

It is argued that the TV show Star Trek alone inspired a generation of scientists. A study revealed that the number of women working in MIT doubled between 1970–1974, with many citing the TV series as an inspiration (Joyrich, 1996). Many astronauts have claimed they were inspired by the series, including Mae Jemison, NASA Astronaut on the space shuttle Endeavor.

When it comes to ocean science, if you asked a marine scientist what inspired them to join the field, you may get answers such as the documentaries of Jacques Cousteau, comic book heroes like Aquaman, or TV shows such as Voyage to the Bottom of the Sea.

The idea behind this project is to promote and facilitate the production of popular artistic and literary projects that incorporate ocean science to promote both ocean literacy and to create more inspirational ocean-related projects.

It is proposed that a series of international workshops be organized to connect ocean scientists with novelists and writers and designers from the: (a) computer gaming; (b) tabletop gaming; (c) TV and movie; and (d) comic and graphic novel industries.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

This project would draw on a combination of U.S. federal experts—in particular, the U.S. National Science Foundation's (NSF) Division of Ocean Sciences and the National Oceanic and Atmospheric Administration (NOAA), but also the U.S. Fish and Wildlife Service (FWS), National Parks Service (NPS), Environmental Protection Agency (EPA), the U.S. Coastguard, the U.S. Navy, and other branches of government with a remit for science outreach to the public about ocean issues and technology—and connect them with the industries.In addition, the project will draw on experts from academia and the marine technology fields.

This project is specifically about making connections between science and technology experts and the creative media industries. The latter will include: publishing; gaming (including game apps); television; movie; comic book and graphic novel industries. Developers, designers, writers, executive producers, and conceptual artists in particular will be invited to the workshops so that science can be incorporated early in the creative process.

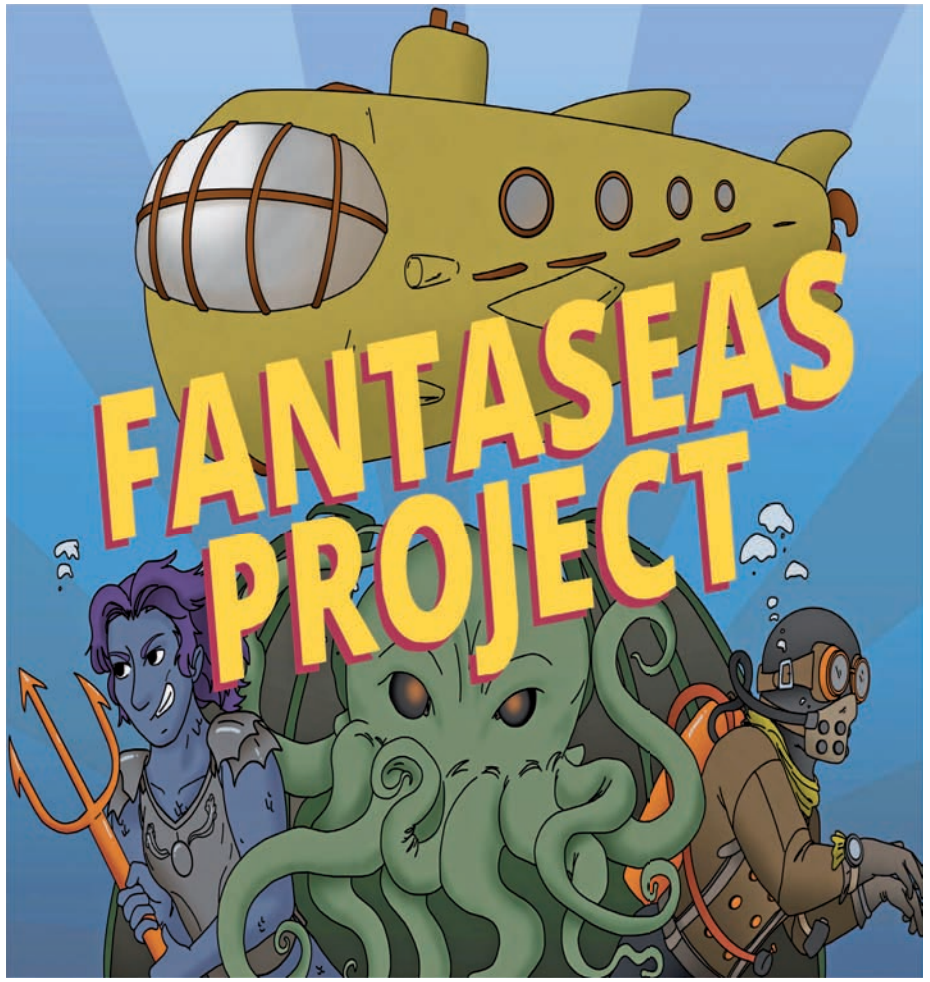

Image by Erin Ziegler Andersen.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

As mentioned above, the project will involve participants from many non-scientific fields from the creative media industries such as designers, conceptual artists, writers, executive producers, set designers, prop creators and so-forth. Getting the science and technology right (or at least scientifically feasible for sci-fi or fantasy projects) on screen will need consultation and feedback from engineers and designers from within the relative media industries in addition to the writers/creatives. For example, what may seem a great idea in a workshop may not be feasible in practice in a studio.

Opportunities for International Participation and Collaboration

Creative industries are international—there are many fledgling TV and movie industries in eastern Europe, Oceania, the Caribbean, Africa, as well as more established industries in India, East Asia, Western Europe and the Americas. Likewise for the computer gaming industry. But, writers and artists are truly global. It's intended that the workshops in this project, and the partnerships, be truly international, with workshops conducted in multiple languages with both an online and in-person component, so that an aspiring writer or artist in even the most remote, low-income country could gain inspiration and expert advice for their projects.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Many female and minority space scientists and astronauts specifically highlight how female and racially diverse role models in Star Trek encouraged them to enter astronomy and other sciences. The fact that the current actor playing Aquaman is of indigenous Hawaiian heritage has inspired ocean activism and conservation in young Hawaiians. A key theme of this project will be to ensure that ethnicities, genders, and backgrounds of ocean science characters are diverse—providing inspiring role models for viewers/readers, especially younger audience members. Imagine, for example, the impact it might have on a young TV viewer to see a smart, heroic female submersible pilot/ marine scientist of color on a hit show!

Reference

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Nature-Based Nutrient Reduction for Seagrass Restoration

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ABSTRACT

Seagrasses provide the following benefits worldwide.

- Habitat for Marine Life
- Nursery for Juvenile Fish
- Food
- Biodiversity
- Carbon Storage (Blue Carbon)
- Ocean Acidification Control
- Oxygen Production
- Sediment Erosion Control
- Nutrient Cycling

Seagrass loss has been persistent for the past 100 years and is now accelerating at 7 percent (21,000 square kilometers) per year. We are addressing seagrass loss resulting from nutrient pollution which is about one third of the total.

The technical objective is to remove at least as much total nitrogen from the sediment and bottom waters to allow restoration with the subsequent successful planting of seeds from nearby meadows.

Our nature-based process starts with the eutrophication-induced restriction on the process to remove excess nitrogen from the top layer of sediment, coupled nitrification denitrification (CND). Decaying organic matter and biogeochemical processes consume enough oxygen to reduce the efficiency and capacity of the CND process.

The solution is to increase the rate of dissolved oxygen flux in the bottom waters. Although science has known this for 20 years, how to do it has been a mystery. To facilitate oxygen dissolution, we will use nanoscale oxygen bubbles mixed with bottom water and delivered to the water/sediment interface.

Vision and Potential Transformative Impact

The challenge of slowing, stopping, and then reversing the accelerating global trend in seagrass loss is formidable and necessary. Such a solution needs to have three necessary components: (1) Impact, (2) Speed, and (3) Low Cost.

Impact is not only the technical requirements of the job but the ability to scale solutions. Our solution addresses seagrass meadows that have been lost due to nutrient pollution. Although this is now a significant amount (7,000 square kilometers yearly) actual projects are anticipated to restore meadows that have been lost for decades.

Speed of adaptive and mitigating solutions is now a necessity. Traditional methods of nitrogen removal from the sediment use wastewater treatment plants that function well but can take 40 years to do it. For moderately impaired sediments we believe we can remove enough nitrogen to be ready for seeding at the end of the first or second year. The process delivers a mixture of nanoscale oxygen bubbles and recirculated bottom water to the water/sediment interface. At this size bubbles dissolve quickly.
Major benefits of nature-based solutions are existing infrastructure in an efficient form at no cost. The natural process has been developed and proven over 100 million years.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The technical proof-of-concept and subsequent scaling we believe are realizable with low risk. While we need help from biogeochemists and marine biologists for technology development and scaling, they should be available with effort, funding, and introductions. We lack financial resources for technology development but are working to obtain them while pressing forward. We view our solution to be applied science and engineering combined with entrepreneurship. At a problem size of multiples of annual seagrass loss of 7,000 square kilometers the scope and scale of the problem require much capital to be fully realized. Our process first reduces the nitrogen concentration to an acceptable level then seeds a target area. Growth of the seagrass meadow requires periodic nitrogen reduction at the sediment/water interface for meadow expansion but no additional seeding.

Public–private partnerships will be necessary to establish financial standards suitable for all parties and the capacity to deliver them.

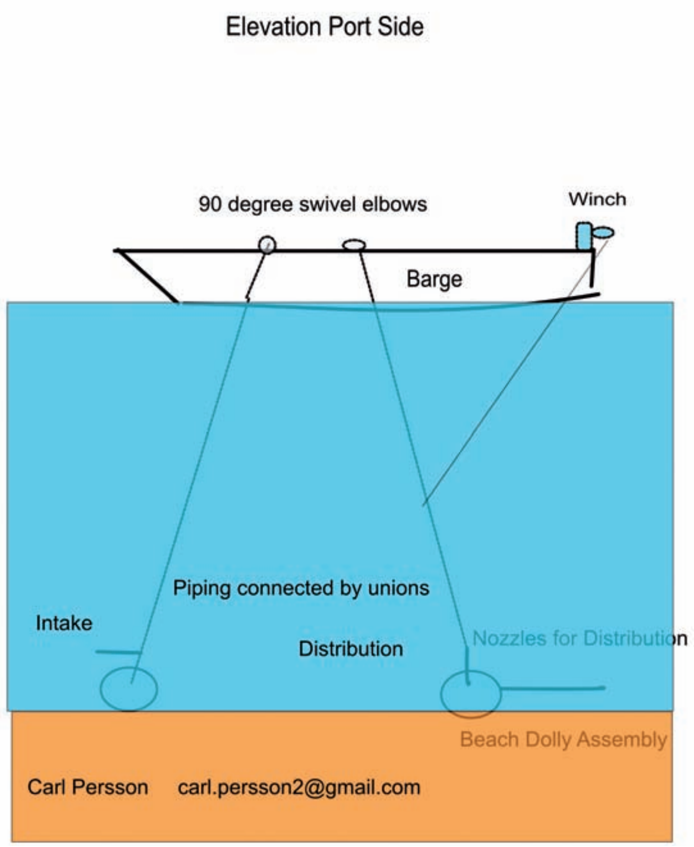

FIGURE 1. Floating system (left side view).

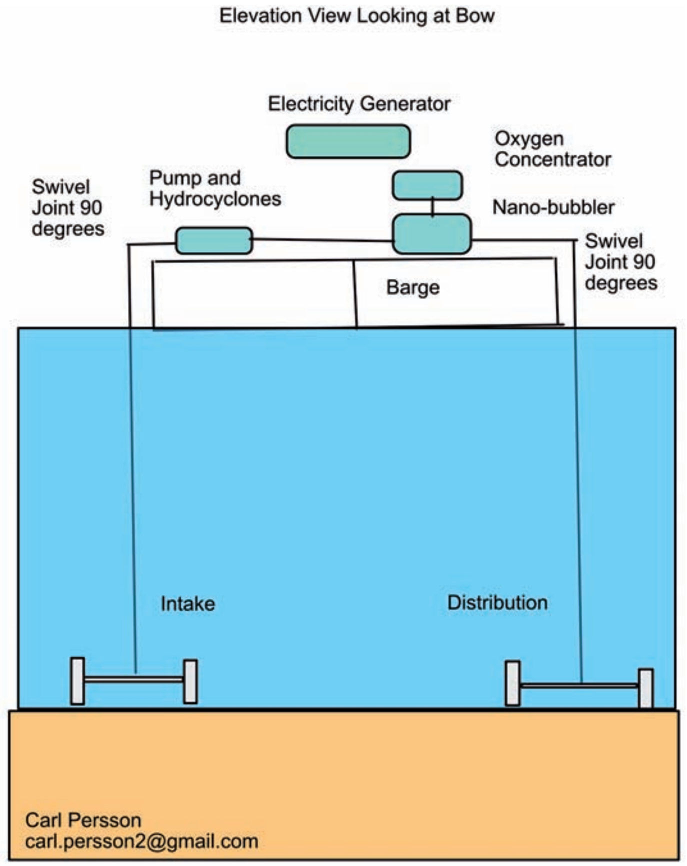

FIGURE 2. Floating system (front view).

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Nano-bubble technology enables our approach. This technology provides oxygen bubbles in the diameter size range of 100 to 200 nanometers. At this size bubbles have neutral buoyancy and are charged such that they repel each other. As a result, oxygen dissolution rates are 5,000 times that of aeration methods originally attempted 20 years ago.

An oxygen concentrator separates oxygen from air at ambient conditions.

For commercial process control we will use IoT connecting sensor information to the Internet. Data collected then can be analyzed and optimized to control the process through AI.

Opportunities for International Participation and Collaboration

Europe has experienced nutrient pollution for many decades resulting to significant seagrass loss. The Baltic Sea is a particularly significant problem area on a world scale. Most of coastal Europe has comparable problems. European academic institutions as well as ocean organizations have significant research experience, expertise, and capacity. This is the best opportunity for our international participation and collaboration.

China offers seagrass loss problems and research capabilities. Many problem areas exist worldwide and represent opportunities in developing countries where seagrass restoration many be even more impactful to local communities. However, we do not have the same level of collaboration capabilities.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The scale and complexity of ocean-related problems need an interdisciplinary approach involving science, engineering, and business. Traditional methods that do not serve us well enough must give way to innovations that do. We must encourage these alternative approaches with the potential to disrupt the status quo and replace it with something better. Disruption here is a business term usually applied to startup companies.

Any success with this approach will increase demand for people with creativity and skills in the kind of problem solving we need. This will include ocean scientists whose science will be applied to our most pressing needs.

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Future Fisheries in a Changing Ocean

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ABSTRACT
Marine fisheries provide protein, income, and employment for millions of people across the world, but future fisheries face multiple stressors, including climate change. To ensure continued flows of benefits from fisheries, we need modern, forward-looking ways of setting sustainability objectives that consider ecosystem carrying capacity, health of fish stocks, societal nutritional and economic needs, and equitable distribution of fishery benefits. Transdisciplinary teams of oceanographers, climatologists, ecologists, economists, data scientists, and decision scientists working together with fishery managers, municipal leaders, fishers, aquaculturists, and seafood supply chain businesses can reimagine sustainable fisheries in a changing world. Through coordinated, distributed research nodes, these types of teams will develop frameworks, information, infrastructure, and application pathways needed to ensure vibrant, resilient fisheries and fishing communities in healthy marine ecosystems in future decades.

Vision and Potential Transformative Impact

We envision transdisciplinary teams of oceanographers, climatologists, ecologists, economists, data scientists, and decision scientists working together with fishery managers, municipal leaders, fishers, aquaculturists, and seafood supply chain businesses to reimagine sustainable fisheries in a changing world. Marine fisheries provided over 84.4 million tons of protein, $230 billion in first-sale value, and livelihoods for 60 million people in 2018 (FAO, 2020). To ensure these benefits continue and are distributed equitably, these teams will identify modern, forward-looking ways of setting sustainability objectives that consider ecosystem carrying capacity, health of fish stocks, multiple benefits derived from wild and farmed fisheries (e.g., protein, jobs, economic, cultural), and how those benefits are shared. The teams will develop metrics and approaches to quantify progress towards these objectives, critically evaluate relevant reference points, and assess factors that influence their achievement. In addition, they will project the future likelihood of reaching desired objectives and evaluate trade-offs among multiple objectives under potential climate, social, economic, and policy scenarios. Resulting computing and modeling infrastructure, knowledge, information, and outputs will support forward-looking policies and decisions at multiple scales to ensure vibrant, resilient fisheries and fishing communities in healthy marine ecosystems in future decades.

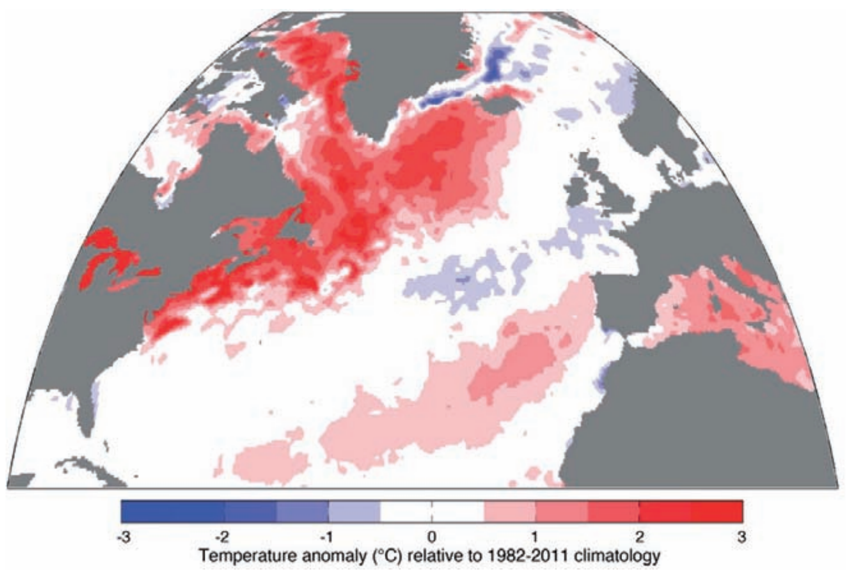

FIGURE 1. Sea surface temperature anomalies for June-August 2012 during a marine heatwave in the Northwest Atlantic that affected fisheries in the Northeast United States.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Achieving transformative approaches to sustaining fisheries in the future will be grounded in recent scientific advances to: (1) enhance ocean observing, (2) improve fishery stock assessments, (3) model fish populations and fisheries in dynamic ecosystems and changing climate conditions, (4) conceptualize fisheries as social-ecological systems, and (5) identify factors shaping and approaches to operationalizing resilience and adaptation in marine fisheries. The work will capitalize on advances in computing capacity and the integration of computing and ecological expertise, as well as expanding initiatives to provide forecasts of ecosystems and fisheries at multiple time scales based on environmental conditions and climate projections. In addition, it will rely upon and continue to build strong collaborations between scientists, fishing industry participants, managers, and community leaders and will develop new public–private collaborations with technology and computing entities.

FIGURE 2. Lobster landing dock in Stonington, ME. Photo by Katherine Mills.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

A broad array of scientific expertise will be needed to address challenges and achieve goals for future fisheries in a changing ocean. Traditional disciplines of oceanography, climatology, and ecology will be necessary, but those scientists will also need to effectively work with economists, sociologists, anthropologists, decision scientists, data scientists, and computer scientists to bring relevant disciplines to bear on this challenge. Moreover, these diverse scientists will need to work not only in parallel, but also in integrated, transdisciplinary teams with one another and with non-scientist collaborators to achieve the necessary scientific advances to support this Ocean-Shot transformation.

Opportunities for International Participation and Collaboration

We envision this effort proceeding through several U. S. research nodes, with parallel teams and nodes in other countries. Each team will focus on fisheries and ecosystems in which they have the most knowledge and experience, but close collaborations will be established across the teams to design and test research, engagement, and application approaches and to continually learn from and contribute to each other's experiences. We have initial international contacts through ongoing research collaborations and advisory roles, and we are eager to elicit broader participation from scientists and partners with shared interests.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The topic we propose to address is one of national relevance as well as global concern. We are confident that future ocean scientists will be eager to contribute to these societally pressing issues and that this research effort will offer unique learning and experiential opportunities. In particular, students and early career scientists will be able to build disciplinary depth and expertise within transdisciplinary teams of collaborators. Such an experience will provide contact and integration with multiple scientific disciplines, societal sectors, and fishery-related stakeholders. As we expect parallel research in multiple countries, we also anticipate opportunities for cross-national collaborations and exchanges.

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The Great Global Fish Count (GGFC): A Potential Project of the UN Ocean Decade

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ABSTRACT

The Great Global Fish Count (GGFC) is a community science project to count fish and then other forms of marine life in coastal and later all waters using loose DNA in seawater (marine eDNA) shed by all animals. The project would distribute small filtration devices to millions of people. The devices would enable participants to take water samples, filter the water, stably preserve the filter with the sediment containing DNA, and post the filters to qualified labs for eDNA analysis. Labs would analyze samples, identify species, and upload data to a project database including Web-based geographical information systems accessible to a mobile app. The collector of each sample would learn the species and quantities of DNA in their sample(s) and have access to information from all other samples. The totality of the data would open countless opportunities for analysts to discover patterns and trends. The project would begin by targeting fish species, because of their societal importance, public interest, availability of high-quality primers to grab relevant sequences, and richness of the DNA reference library of fish sequences. Later in the decade the project could expand to all vertebrates (including marine mammals), mollusks, crustaceans, and other taxa, perhaps adding one major group each year.

Vision and Potential Transformative Impact

The GGFC could measure the baseline and changes in the totality of the distribution and abundance of most known fish in the Anthropocene oceans, and potentially other taxa. The proposed scale of use of eDNA is unprecedented. The largest eDNA efforts so far involve a few hundred samples, while the GGFC would involve millions or tens of millions. The proposed scope, covering entire coastlines, basins, and the global ocean is also new.

The GGFC could greatly advance knowledge of impacts of fishing and aquaculture, urbanization of coast lines, pollution, offshore energy extraction, efforts to restore and protect habitat, climate change, and other factors. eDNA can illuminate the invasive, elusive, or endangered as well as the common.

The R&D component of the program would speed improvement and adoption of best practices. Enhanced adoption of marine genomic techniques could be a major outcome, as well as enhancement of marine genomic reference libraries. The number of people qualified for careers in marine 'omics should grow. The program would foster initiation of time-series. Entrepreneurial companies providing eDNA and other services in marine genomics should increase in number and scale. DNA results should become affordably available to large numbers of people for identification of presence of marine species in near real-time. The GGFC should also produce surprises about distributions and abundance.

Ultimately, smarter boundaries in space and time for marine protected areas could be an outcome, and identification of biodiversity hot spots and trouble spots. Detection and documentation of ecological recovery should become more reliable.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

No U.S. or international networks yet exist for systematic advancement of marine eDNA. The program does not face a big problem of entrenched structures. The GGFC could create much of the national and global infrastructure for eDNA and marine genomics more broadly. It could lower costs and standardize practices.

The GGFC meshes with NOAA's Genomics Road Map, marine genomic and biodiversity initiatives of the Smithsonian Institution, and archival initiatives such as the Ocean Genome Legacy Project.

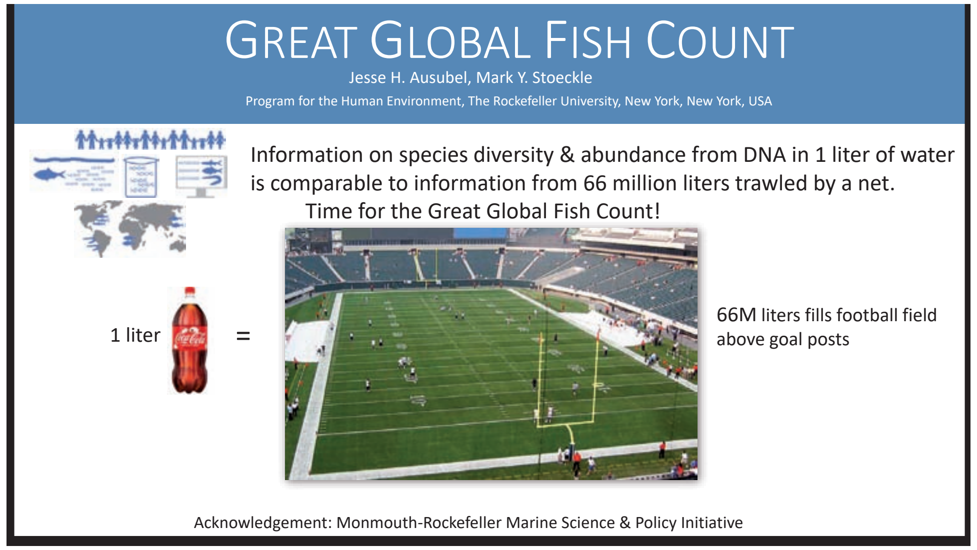
Within the U.S. government, most participants in the National Ocean Partnership Program should take an interest, including many parts of NOAA, the Office of Naval Research, National Science Foundation, and DOI's Bureau of Ocean Energy Management. State coastal and environmental agencies might have much to gain, for example, by enhancing survey efforts for salmon in the Northwest or cod in the Gulf of Maine.

Aquariums and natural history museums would have much to contribute and to gain from the success of the GGFC.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

The convergence of genomics with information technologies and geographical information systems makes the program newly feasible and available for global participation.

Suppliers of goods and services in the biotech industry such as New England Biolabs, Illumina, GeneWiz, and ThermoFisher/Applied



Biosystems would be valuable partners, as would companies making and operating drones, which could extend sampling, especially far from shore and in deep water. Shipping companies such as FedEx and UPS might provide useful services, as well as IT companies with cloud storage.

Cruise lines, resorts, and others involved in marine and coastal leisure industries might also welcome the program, to which they could contribute samples and with which they could entertain their guests.

An important ethical advantage of the program is that it does not require collection of living organism or stress animals.

Opportunities for International Participation and Collaboration

The United States and France, with far the largest Exclusive Economic Zones, must play leadership roles together with other nations combining strong competence and shoreline. Internationally, nongovernmental organizations, including POGO, SCOR, and SCAR (for Antarctica) could multiply success of the program by fostering eDNA science, standards and protocols, sampling, and big data analyses. In the North Atlantic ICES and in the Pacific PICES could use GGFC to develop eDNA standards for fisheries and other surveys. UN FAO (Fisheries Division) and other agencies could engage in capacity-building around GGFC and benefit from its findings, which should contribute to their reports on the State of Fisheries and Global Oceans and marine sections of IPCC and IPBES reports. Management of the GGFC would probably involve an international scientific steering committee as well as national or regional committees, and working groups concerned with technology development, standards and protocols, data science, engagement, and other themes.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers and Technologists

Anyone with a cellphone should be able to benefit from the GGFC and its outcomes. People of all ages can make valuable collections and learn from their own samples. Recreational boaters and fishers would have wonderful opportunities. Adoption of the GGFC as a Decade Project at the 2022 Berlin conference would be an initial milestone. 2024 might be the year of the Great Count. A conference in 2025 would highlight important results and inspire continuing efforts. Overall, the GGFC should develop global capacity to sense and know the oceans and encourage new generations of ocean scientists and stewards.

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The Coral Reef Sentinels Program: A Mars Shot for Blue Planetary Health

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ABSTRACT

Up to 90% of global coral reefs are predicted to be severely degraded by 2050 under "business-as-usual" scenarios. To meet the scale and scope of this challenge, we propose designing and demonstrating a multi-modal system that can incorporate data from remote sensing (satellites, aircraft, and aerial drones), acoustics, genetics, sensor arrays, and low-cost imaging systems. The latter will be collected by low-cost smart sensing and autonomous underwater vehicles (AUVs) guided by adaptive sampling modeling software and rapidly analyzed using automated machine learning systems. Development and deployment will be linked to extensive and diversity-enhancing training programs. The Coral Sentinel System will be globally deployed to enable rapid-response adaptive management and to build public engagement in conservation interventions to save coral reefs.

Phase 1 (Year 1) will involve testing assumptions, coalition building, fundraising, and initial system development. Phase 2 (Years 2-4) will focus on engineering and development with a pilot deployment in the Caribbean. Phase 3 (Years 5-6) will involve system expansion and iteration along the Tropical Eastern Pacific corridor. Phase 4 (Years 7-10) will involve global deployment to over 50 reef sites. This will lead during the following decade (Phase 5) to provisioning of low-cost Sentinel systems to coastal communities globally.

Vision and Potential Transformative Impact

Coral reefs are the most biodiverse ecosystem in the ocean, providing habitat for millions of species, supporting over half a billion people, and providing billions of dollars in income annually. However, coral reefs are being lost at an unprecedented rate, which is accelerating due to mass bleaching and ocean acidification, exacerbated by local human impacts.

Our ambitious, achievable, and transformative Coral Reef Sentinels program will deliver actionable data and knowledge about the health and state of coral reefs in near-real time and enable conservation interventions to protect these reefs from harm while ensuring local ecological, economic, and cultural health. We will design and demonstrate an integrated, scalable monitoring, modeling, and decision-support system for reef science and conservation involving remote sensing (satellites, aircraft, aerial drones), sensor arrays, acoustics, eDNA, and imaging systems on fleets of low-cost AUVs powered by artificial intelligence. It will be deployed on reefs around the world to measure coral reefs' responses to environmental changes and efficacy of conservation interventions guided by information processed in near-real time. This will facilitate rapid-response adaptive management, enhance public awareness about ongoing changes to coral reefs, and build local capacity to monitor and respond to changes to local reef systems.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The Coral Sentinel program brings together scientists, engineers, computer scientists, and conservationists from the Smithsonian Institution, NASA Ames, the Scripps Institution of Oceanography, the University of California San Diego, the California Academy of Science, and Arizona State University, as well as public–private partnerships with Conservation X Labs and Conservify. We also have partnerships with social scientists, environmental lawyers, and conservationists at the Waitt Institute and the Smithsonian's Healthy Reef Initiative.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

We are engaging computer scientists with expertise in AI and machine learning (UCSD, NASA Ames, University of Sydney); engineers from non-profits (Conservation X Labs and Conservify), and from NASA Ames, the University of Sydney, and the University of Haifa; and social scientists, environmental law experts, and conservationists from the Waitt Institute and the Smithsonian's Healthy Reefs Initiative. Through citizen science projects (NASA's NeMo Net, Squiddle) and TV and film productions about the project (Nalu Creative, Luc Hardy, James Nikitine and Fabiano D'Amato), we will educate and motivate the public globally to join in Sentinel efforts to save coral reefs.

FIGURE 1: The Coral Sentinel Program will use a combination of new and emerging technologies to enable reef monitoring in near-real time, creating an early warning system to detect ocean acidification, warming, hypoxia (low oxygen), mass bleaching events, diseases, invasive species, and in turn, alert and empower reef managers and coastal communities to take action. The program's suite of technology will include cutting-edge remote sensing devices, including satellites and drones, that will anchor our work in broad-scale reef maps and oceanographic conditions. In addition, a self-driving boat on the water's surface will create 3D maps of shallow reef areas while using a custom software system to synthesize multiple data streams. The adaptive software will guide the deployment of swarms of low-cost autonomous under-water vehicles (AUVs). These AUVs will be outfitted with sensors to monitor key environmental variables (temperature, oxygen, salinity, pH, alkalinity, nutrients, light), a mobile DNA barcode scanner to analyze DNA sampled from the surrounding seawater and state-of-the-art 3D cameras to collect high resolution 3D maps of reefs. These maps will capture data on such a fine scale that scientists will be able to monitor the growth and mortality of individual corals over time. AUVs will also be modified to become seafloor observing systems (Coral BOSS) that can remain on the ocean floor for multiple days to measure the diversity and biomass of fish and invertebrate communities while monitoring key environmental parameters. The vehicles will regularly return to a surface vehicle to get recharged—much like an electric car charging station—and upload data to the cloud via satellites. Data will then be rapidly analyzed using a machine learning system and translated into actionable information for local stakeholders and policymakers. Illustration by Paulette M. Guardia.

Opportunities for International Participation and Collaboration

Currently we have international partners at the University of Sydney, the University of Haifa, Bar Ilan University, and at the Technion. Through our collaborations with Smithsonian's Healthy Reef Initiative and the Waitt Institute we will engage and collaborate with coastal communities at over 50 reef sites globally. Our ultimate goal is to

FIGURE 2: Photograph of a healthy Caribbean Acropira cervicornis reef from Bocas del Toro, Panama. By eventually working with local partners, conservation groups and reef restoration programs at over 50 major reef sites globally, scientists will develop a system that can guide conservation interventions to change the trajectory of reef decline. Increasing the health of reefs globally will be essential for climate change adaptation and to ensure thriving blue economies for coastal communities. Photo by David I. Kline.

provide low-cost automated technologies that coastal communities around the world can use to protect their local coral reefs. Our global partnership of leading conservation organizations, research institutions, technology providers, and civil society groups will develop, implement, and ensure permanent long-term effectiveness of this program.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The Coral Sentinel program will build on partnerships with coastal communities globally to provide technology and training to empower better local management and protection of coral reefs. At all partnering institutions we will offer fellowships to next-generation ocean scientists, engineers and computer scientists, with a focus on growing diversity, to support and enhance global efforts to save coral reefs. We also plan to provide training and opportunities for collaboration for local ocean scientists in every country where we work, to empower and train the next generation of scientists in countries around the world.

Funding for this work was provided by the Rohr Family Foundation, The Rohr Reef Resilience Program: Drivers of Coral Reef Resilience across the Tropical Eastern Pacific Corridor (DIK, SS, LL, SC); Schmidt Marine Technology Partners (AD); and the Moore Foundation (AD, PB, SS, II). FluidCam was supported by NASA Earth Science Technology Office (ESTO) Grant ATI-QRS-14-0010; MiDAR was funded in part by NASA 2015, 2016, and 2017 Center Innovation Fund (CIF) grants, and NASA ESTO Advanced Information Systems Technology (AIST) Grant AIST-QRS-16-0004 and AIST-16-0031; NeMO-Net was supported through ESTO AIST-16-0046 (VC). NOAA, CoralNet: Tackling Bottlenecks in Coral Reef Image Analysis with Next Gen Deep Networks for Photographs to Large Mosaics (DK). NOAA, Quantifying Coral Reef Net Calcification Capacity and Vulnerability in the Context of Ocean Acidification (DK, AA). Summit Foundation: "General Program Support for the Healthy Reefs for Healthy People Initiative" (MM). Tennenbaum Marine Observatories Network (JED).

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Data-Driven Coral Reef Rehabilitation Using New Biomimicking, Advanced Materials Artificial Reefs

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ABSTRACT

Globally, artificial reefs (ARs) are being increasingly used as a coral reef restoration strategy, and ARs made from conventional substrates (e.g. metal, concrete) have had limited success for coral reef conservation due to structure size and lack of pre-deployment engineering. To curb further deterioration on reefs, technological advances in restoration methods must be quickly tested and applied on a large scale. Here, we present the results of the first IntelliReefs biomimicking “Oceanite” nanotechnology ARs. We compared benthic community composition on three Oceanite ARs 14 months after deployment in Sint Maarten. We also examined fish abundance, diversity, and behaviour on the ARs. The results from this study suggest that Oceanite can enhance local biodiversity, attract coral recruits, provide food and protection for large fish communities, and develop a healthy early coral reef community in 14 months. IntelliReefs' future research will focus on large-scale deployments and further development of site-, species-, and function-specific substrates to optimize AR conservation goals and increase project success. Our Ocean-Shot will deploy durable, bio-enhanced reefs that build resilience to climate change, increase economic benefits, and coastal protection for seaside communities. Oceanite can further be customized for specific stressor mitigation (e.g., pathogens, warming, acidification, reduced water quality, invasive species).

Vision and Potential Transformative Impact

IntelliReefs’ vision is to increase human food, economic, and coastal security in the face of climate change by providing shoreline protection systems and habitat enhancement solutions for degraded ocean ecosystems. Through biomimicking infrastructure, we will also provide new opportunities for scientific experimentation and platforms for local fisheries and ecotourism businesses.

IntelliReefs has developed the first line of nanotechnology-enhanced marine substrates specifically engineered to protect coastlines, promote biodiversity, and accelerate reef growth through mineral matrices called “Oceanite”. Oceanite can be fine-tuned down to the nanoscale for site, species, and function requirements, increasing the ROI and high-impact results. Traditional marine concrete is toxic to ocean flora and fauna and less durable than Oceanite. Using biomimicry, we developed IntelliReefs to mimic the architecture and habitat of a natural coral reef, attenuating wave force and providing the building blocks for rapid and healthy coral growth.

Oceanite provides a living substrate for ocean infrastructure and allows us to bioengineer climate change solutions for oceans. Research has shown that live coral reef cover on wave attenuation structures can dissipate wave force up to 97%, mitigating billions of dollars in coastal damage from storms and erosion annually. IntelliReefs aims to protect coastlines quickly by rebuilding large reef structures that have been lost due to climate change, while providing bio-enhancing, sustainable habitat customized for commercially and biologically important species.

FIGURE 1. Representative photos of invertebrate communities on horizontal and vertical surfaces of IntelliReefs’ Oceanite artificial reefs after 14 months of deployment (January 2020). Photographic and videographic surveys reveal IntelliReefs can foster A) rapid coral settlement and recruitment B) fish and invertebrate sheltering, C) high biodiversity and crustose coralline algae, and D) fish feeding (every ~15 seconds) and aggregating.

FIGURE 2. Recent diver observational photos of IntelliReefs in Philipsburg, Sint Maarten after 28 months underwater. Preliminary diver surveys suggest that coral recruitment has increased 4-fold on this IntelliReefs structure in the last 14 months. Photos from the Sint Maarten Nature Foundation, March 24, 2021.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The proposed project would allow us to fill a national and global niche in coral reef restoration. Currently, there is no other company on the market that has the ability to pre-seed and customize substrates by site, species, and conservation goal. Further experimentation is necessary in order to implement the large-scale habitat restoration efforts that are needed globally. IntelliReefs has the manufacturing capability to build back entire swathes (hundreds of meters to hundreds of kilometers) of degraded marine habitat to protect coastlines, and the potential to accelerate coral growth, mitigate undesirable species growth, and buffer for environmental and anthropogenic stressors is unprecedented.

IntelliReefs has conducted 100+ discovery interviews with domestic and international companies and organizations related to underwater construction, reef remediation, tourism, aquaculture, and government. The Sint Maarten project will mark the completion and analysis of our large-scale field testing. Small variations in mixture performance for coral growth in R&D will have high-impact consequences in the field when deploying large-scale, cast artificial reefs to restore coral ecosystems. As a cladding application onto existing marine infrastructure, IntelliReefs’ products will facilitate colonization by desired and diverse flora and fauna to attain global sustainable development goals (SDGs).

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

IntelliReefs harmonizes conservation objectives with environment and business. We have three branches that work together to meet marine restoration and development needs: biological and material science, design and manufacturing, and business/marketing. The science team consists of nanomaterial scientists and coral restoration specialists, delivering conservation solutions that address community identified needs. Our science teams collaborate with and publish with researchers from academic institutions in the United States and abroad. Our design and manufacturing team are experts in artificial reef design, manufacturing processes, materials testing, and deployment. Our business/marketing team coordinates educational awareness campaigns, manages client relations to enhance project ROI.

Opportunities for International Participation and Collaboration

The ocean has lost about 50% of coral reef ecosystems due to pollution, climate change, and destruction of habitat. IntelliReefs works domestically and internationally to restore and revitalize reefs through innovative, data-driven solutions. We cultivate trust in communities by inspiring collaborative, ocean-forward partnerships and research projects. Our commitments to local eco-education demonstrates our respect for their environment, ensuring our actions preserve ecosystem integrity and biological complexity for future generations. We believe that interdisciplinary conservation projects, partnering with local conservation organizations, businesses, and governments will be the most successful means of protecting nature and accelerating positive, long-term change.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

IntelliReefs works with conservation organizations, academic institutions, international policy entities (e.g., GLISPA), local schools, tourism entities, and global ocean foundations. IntelliReefs’ design and testing is interdisciplinary by nature, and many of the products we are developing use principles of nanotechnology and advanced material science. Ocean conservation and restoration will not be solved by biologists alone. We firmly believe that innovative, disruptive technologies originate when scientists from different disciplines work together. IntelliReefs also strives to inspire harmony between science and the community that it serves, using deep-rooted cultural knowledge and priorities to inform conservation and business initiatives.

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The Estuarine Ecological Knowledge Network: Future Prospects

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ABSTRACT

Estuaries are profoundly rich, diverse, and complex ecosystems, and crucial to the overall health of Earth's oceans. Estuarine ecological complexity is matched by tremendous human cultural diversity. In the United States, millions of people live in estuarine environments from the Gulf of Mexico to the Arctic—many of whom directly depend on the productivity of marine resources in both commercial and subsistence fishing activities. Yet, estuaries are also among Earth's most threatened landscapes against the backdrop of global warming, sea-level rise, agricultural and industrial pollution, habitat loss, overfishing, and so on. This represents a looming disaster for our oceans at a global scale. The Estuarine Ecological Knowledge Network (EEKN) is based on the idea that fishing communities living within major estuaries are the key to ensuring the health of global oceans. Coastal fishing communities have vast accumulations of ecological knowledge about the functioning of estuarine ecosystems and interact with those ecosystems in intimate ways on a daily basis. This network is designed to connect coastal communities in monitoring the health of estuarine ecosystems and in using traditional ecological knowledge to develop strategies for enhancing ecosystem health and resilience.

Vision and Potential Transformative Impact

Estuarine communities interact with their environments closely through fishing activities at an enormous range of scales: from multinational seafood corporations to entrepreneurial boat captains to subsistence-level and recreational fishermen. These various scales of fishing activity entail the collection of different but overlapping kinds of information about the environment. Above all, fishing communities bring to bear vast stores of traditional ecological knowledge accumulated over countless generations and they are continuously monitoring the ecosystems upon which they depend. While ethnographic studies of estuarine fishing communities contributed to marine conservation and coastal restoration efforts, the full potential of this body of this ecological knowledge and interaction has not been realized. This project seeks to connect coastal communities—both with each other and with marine scientists—in gathering information about the health of estuaries and in developing solutions in enhancing the resilience of both ecological and socioeconomic systems. In this way, the EEKN can identify "red flags" in terms of the health of coastal ecosystems and can help steer policy decisions in order to build healthier oceans and more productive fishing economies.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The EEKN has great potential in fostering public–private partnerships involving the commercial fishing industry, indigenous peoples, social scientists, local/state/federal policy makers, university and government scientists, NGOs, and so on. While some of the above relationships have been contentious historically, the EEKN seeks to build cooperation in enhancing the health of estuaries and in recognizing the inherent connectedness of ecological, economic, and social systems. For example, the EEKN could unite the commercial fishing industry, marine scientists, and indigenous groups in developing strategies for fishing more efficiently, reducing bycatches, adding value to catches, and otherwise helping fishermen make more money while reducing their ecological footprint. Similarly, as many state and federal coastal restoration infrastructure projects have suffered from a lack of support at the local level, the EEKN could provide guidance about how to design large-scale coastal infrastructure in ways that minimize impacts on fishing returns and enhance the overall health of estuarine ecosystems.

FIGURE 1. Handline fisherman in South Plaquemines Parish, Louisiana, with a large black drum (*Pogonias cromis*).

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

From a scientific standpoint, the EEKN project emphasizes engagement with the social sciences, especially anthropology, sociology, and economics. Perhaps more importantly, this project also fundamentally involves the voices of underrepresented coastal community members, especially small-scale commercial and subsistence fishermen, and especially indigenous groups. From a technological standpoint, we also anticipate the development of a range of communication tools related to the "citizen science" aspects of the EEKN project. This would include, for example, the development of smart phone applications for collecting and communicating scientifically relevant observations about estuarine environments—as well as fishing tactics, real-time seafood prices, and other economically useful information.

Opportunities for International Participation and Collaboration

At the global scale, estuaries are major hotspots of both ecological and cultural diversity, as well as being centers of human settlement and economic activity. We envision the EEKN as an international effort, potentially involving estuarine communities from the equator to the poles. From the scientific standpoint, this project would involve university and government scientists from many different nations. In recognizing the role of oceans as a kind of global commons, the EEKN would also connect indigenous communities, fishing interests, and policy makers from around the world in making better informed decisions about the management of estuarine ecosystems.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Perhaps the most important aspect of the EEKN project is its involvement of estuarine community residents, and especially indigenous peoples, in the scientific study of marine ecosystems—with a crucial goal of that involvement being the integration of profoundly under-represented groups into marine science. This relates to our current moment of reckoning in terms of cultural diversity in the sciences and it is in keeping with goals of the United Nations Decade of Ocean Science for Sustainable Development. We hope that the EEKN will play a role in bringing about a diverse new generation of ocean scientists and policy makers.

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Meeting Protein and Energy Needs for 10 Billion People While Restoring Oceans

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ABSTRACT

Shellfish and seaweed farming provide resources, opportunities, and solutions to address a wide range of seemingly intractable global problems. Installed and managed properly, aquaculture operations can be restorative to ocean environments, counter climate change, and relieve pressure to farm sensitive terrestrial environments. For these reasons, there is growing social acceptance and political pressure for marine aquaculture expansion, and State, Federal, and International, as well as eNGO-led initiatives are underway. Now is the time to invest in multi-disciplinary science-based teams that can signpost the sustainable pathway for marine aquaculture by developing monitoring and modeling tools and protocols for measuring associated ecosystem impacts and beneficial services. The yield on that investment will be healthy food and more carbon-neutral bio-fuels grown in ways that help heal our oceans. A sustained commitment by the United States now to develop the science and technology for future ocean farms will find an enthusiastic audience in young researchers and technologist around the world, who seek better ways to improve people's lives through their science and problem solving.

Vision and Potential Transformative Impact

Farming the oceans, or marine aquaculture, is a logical step to enhance production of protein and bio-fuel feedstocks with a smaller ecological footprint than is possible on land. Without a significant shift to marine farming we may deplete most of Earth's ecologically sensitive lands and biodiversity via expansion of terrestrial farming for a projected population of nearly 10 billion by 2050. Our current agricultural practices also contribute nearly 30% of anthropogenic greenhouse gases. Most marine aquaculture emits far less per unit output, and can sequester carbon and enhance water quality. Our vision for marine aquaculture is to be as much an environmentally restorative practice for stressed marine ecosystems as it is a supply of human food and bio-fuels.

The logical aquaculture species to expand are shellfish and seaweeds that don't require any artificial inputs or feed. Both can help remove excess carbon and nitrogen from coastal waters. Shellfish produce healthy proteins, while seaweeds produce complex carbohydrates and micronutrients important to human and livestock health, and potential feedstocks for bio-fuel. Despite many years of moderate scale aquaculture, there are still scientific questions to be answered and social barriers to be overcome before marine aquaculture can fulfill its full potential.

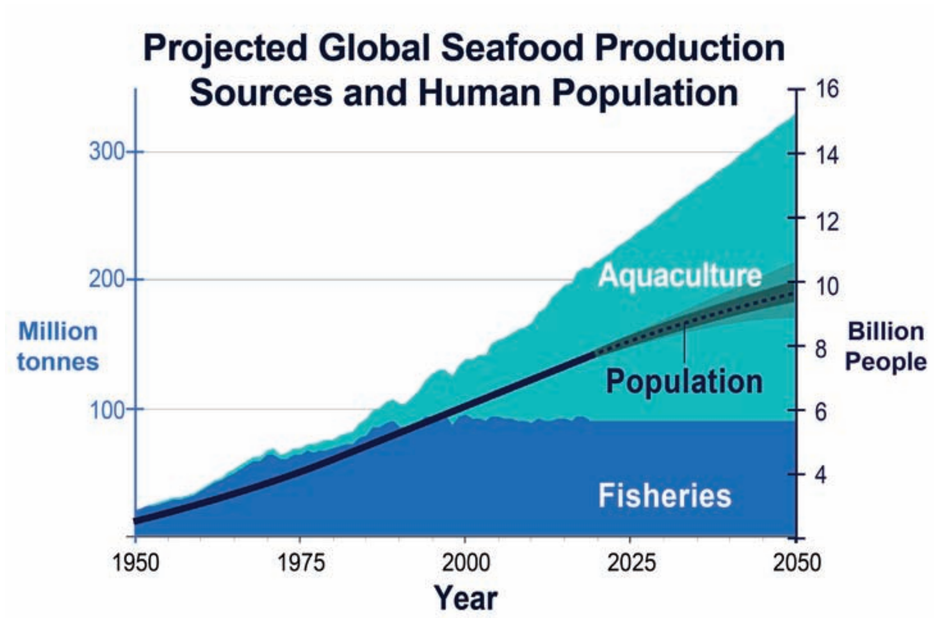

FIGURE 1. Adapted from: United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Highlights (ST/ESA/SER.A/423); and FAO FIGIS, OECD-FAO Agricultural Outlook, Rabobank 2019. https://research.rabobank.com/publicationservice/download/publication/token/hhUMgJyn9L5GVd7zYki2.

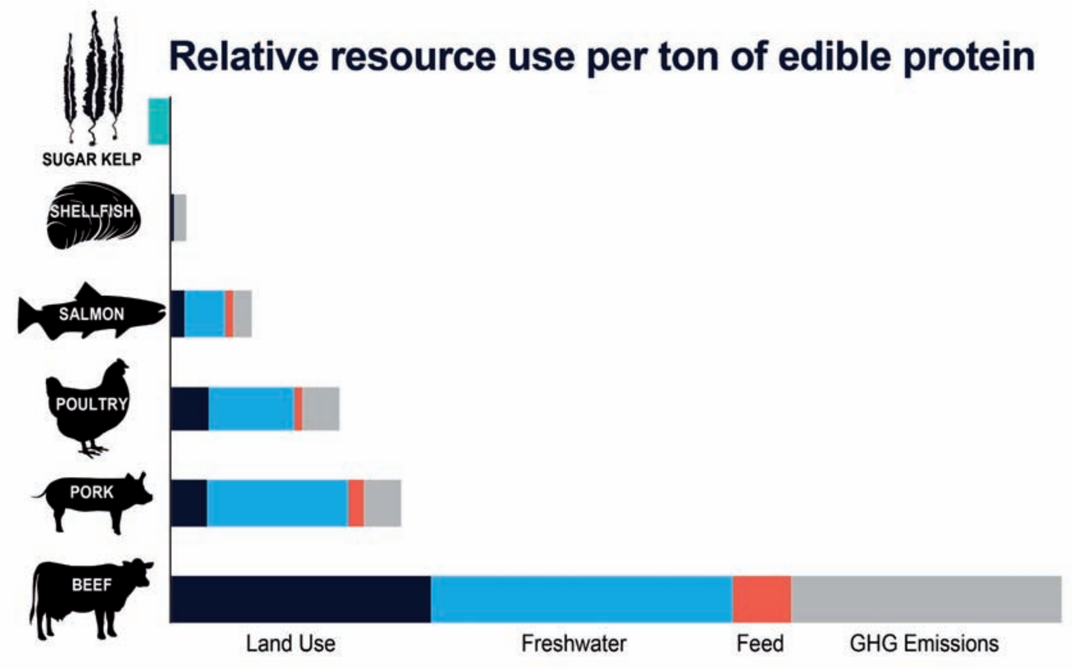

FIGURE 2. Adapted from: Pahlow, M., van Oel, P.R., Mekonnen, M.M., & Hoekstra, A.Y. 2015. Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. Sci. Total Environ, 356:847–857. https://doi.org/10.1016/j.scitotenv.2015.07.124 and Waite, R., Beveridge, M., Brummett, R., Chaiyawannakarn, N., Kaushik, S., Mungkung, R., … Phillips, M. 2014. Improving Productivity and Environmental Performance of Aquaculture. Working Paper, Installment 5 of Creating a Sustainable Food Future. Washington, DC: World Resources Institute (WRI).

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Aquaculture is the fastest-growing food production sector globally. U.S. research and technology development has enabled much of this growth, even though U.S. aquaculture output has lagged the global industry. Currently, shellfish and seaweed aquaculture are a small fraction of U.S. agriculture production, but shellfish farming has quintupled regionally in the last 10 or 15 years, while seaweed production has doubled every year or two over the last five.

A recent Executive Order prompted NOAA to streamline regulations and create Aquaculture Opportunity Areas in Federal waters. The AQUAA Act now pending in Congress will provide more resources for marine aquaculture expansion, including aquaculture research. The DOE has invested about $50M in the last three years in the MARINER Program to develop tools and networks for fostering sustainable seaweed aquaculture. Several members of this Ocean-Shot have already designed and/or implemented aquaculture projects in the United States and internationally.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Optimizing the siting, design, engineering, husbandry, harvesting, and ecosystem stewardship of large-scale future ocean farms will require collaboration across many disciplines and industries. Sectors outside the traditional ocean sciences that can play a key role include agriculture, breeding and genetics, robotics, and biofuel processing, as well as naval architecture and the offshore industry. Multi-disciplinary teams can signpost the sustainable path by early development of monitoring and modeling tools and protocols for measuring ecosystem impacts and services (e.g., ocean acidification, nutrient extraction/deposition, carbon sequestration, impact or enhancement of fishery resources) associated with marine aquaculture.

Opportunities for International Participation and Collaboration

International eNGOs like The Nature Conservancy and World Wildlife Fund are already supporting initiatives to promote shellfish and seaweed marine aquaculture, and investing in research and enterprises. Oceans 2050 Foundation is a collaborative international initiative that cites Regenerative Ocean Farming and Blue Carbon Sequestration as two of its objectives. Foundations with considerable resources like Jeff Bezos's Earth Fund are making major international investments in seaweed farming as a nature-based climate solution. All these initiatives and several more in Europe and Asia-Pacific regions require tools this Ocean-Shot develops to verify or certify the intended environmental benefits derived from aquaculture projects.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

U.S. scientists and engineers are global leaders in the discovery and understanding of fundamental ocean processes, and have partnered with agencies, researchers, and indigenous people around the world to advance aquaculture technologies. A sustained commitment by the United States to develop the science and technology for future ocean farms will find an enthusiastic audience in young researchers and technologist around the world, who seek better ways to improve peoples' lives through their science and problem solving. Helping feed and power the world while restoring the ocean will be a clarion call to some of the best minds of this and future generations.

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Transforming Ocean Science: Fostering a Network for Cooperative Science Research on Commercial Ships (Science RoCS)

Magdalena Andres, **Kerry Strom**, and **Leah McRaven**, Woods Hole Oceanographic Institution (WHOI)

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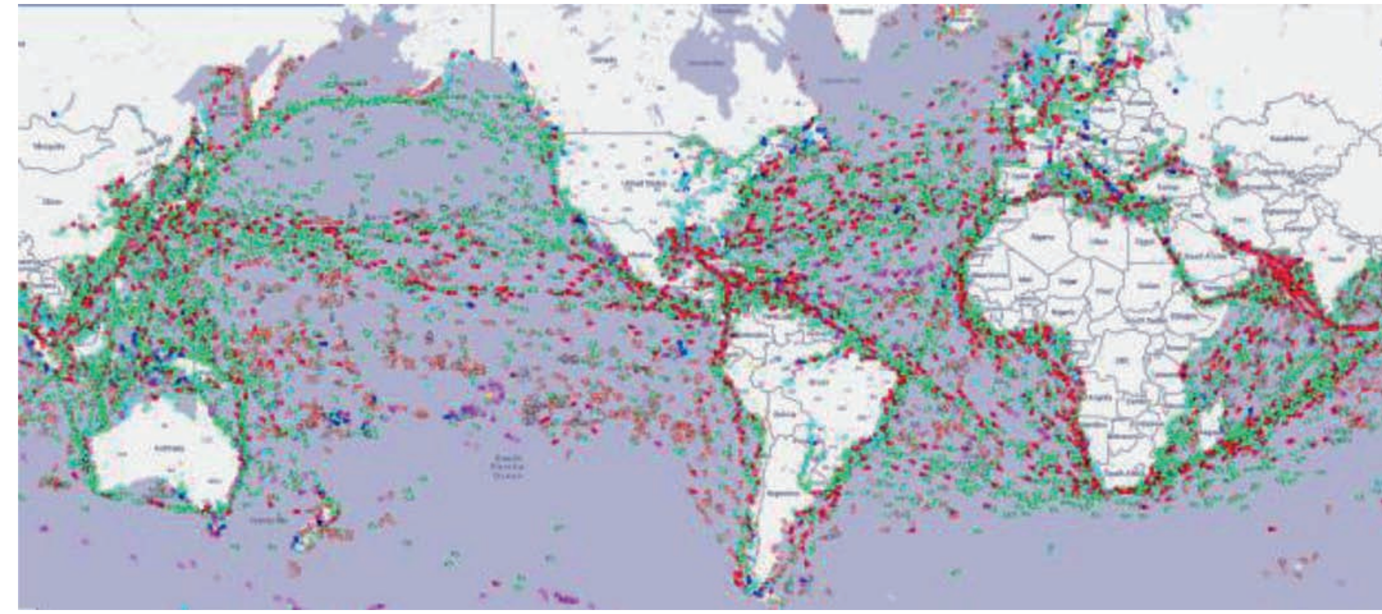
ABSTRACT

Our goal is to transform ocean science through industry partnerships with commercial shippers, creating "integrated observing platforms" with a global reach that will revolutionize the science community's ability to characterize variability in ocean physics, chemistry, and biology across spatial and temporal scales. For the past 100+ years, oceanographers have been able to directly access just a fraction of the global ocean. With only a few dozen research vessels worldwide versus more than 50,000 commercial vessels in operation today, and industry eager to participate in ocean science, the environment is brimming with opportunities. We envision a future where commercial vessels are, as a matter of course, designed and built with a suite of scientific sensors to measure water properties and currents, as well as chemical and biological parameters optimized for a vessel's trade route to address societally relevant questions, with the data disseminated broadly to all stakeholders. Targeted collaborations between science and commercial shippers have existed for decades and the foundation has been laid. Now it is time to build on this experience by using the science community's vast network, relationships, and expertise in sensor technology and science to make data collection on commercial ships the new norm.

Vision and Potential Transformative Impact

We envision an integrated approach to observation of the global ocean on a regular and long-term basis in partnership with the shipping industry as an essential component of the Global Ocean Observing System (GOOS). The challenge here for Science Research on Commercial Ships (Science RoCS) is threefold: fostering cooperation between the shipping industry and the scientific community at a level that will be transformative for societally relevant ocean science; promoting cross-disciplinary ocean science by simultaneously collecting multiple data streams near the air/sea interface (via meteorological sensors and the ship's seawater intake) and within the water column (via acoustic sensors and deployment of autonomous sensors); and spurring a technological revolution in observational oceanography by developing new turnkey, maritime-industry-appropriate scientific equipment. The resulting freely distributed data will be a fundamental resource for understanding the climatic state and health of our planet and will also provide systematic ground truth information about the state of the ocean surface and lower atmosphere to interpret and assess remotely sensed data and numerical model output. This transformative impact will be bolstered by cooperation of those within the scientific community—comprising scientists, engineers, data managers and research vessel operators—as well as close coordination with commercial vessel operators and federal funding agencies.

Science RoCS Commercial Collaborator Vessel, Wallenius Wilhelmsen.



Worldwide vessel traffic: 55,000 commercial vessel vs. orders of magnitude fewer research vessels. Credit: https://www.marinetraffic.com, screen shot.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The global shipping industry is undergoing a technological revolution and is showing a growing commitment to good stewardship of our oceans. Motivated by the emerging opportunities, an ad hoc group from the science community—comprising scientists and engineers from academic and federal institutions, as well as data managers and vessel operators from the oceanographic research fleet—is working to actualize the vision of the OceanScope Report, which was presented at OceanObs '09 and reaffirmed at OceanObs '19 (http://www.scor-int.org/Publications/OceanScope_Final_report.pdf). This cross-institutional group seeks to expand grassroots efforts within the science community and to cultivate connections with a shipping industry eager to cooperate. Building on the science community's successful cooperation with several shipping companies, the group is contacting additional potential industry partners with ties to international shipping consortia, identifying commercial routes of scientific interest, compiling information about state-of-the-art sensor technology and data dissemination, entraining stakeholders, and identifying potential avenues for federal funding for scientific infrastructure.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Working in partnership with industry to collect and disseminate large oceanographic datasets will entrain three sectors within global shipping: vessel owners/operators, manufacturers of marine instrumentation, and developers of vessel data management systems. Preliminary meetings with ship owners to discuss installing scientific equipment on existing vessels and including instruments in new builds is being met with enthusiasm and has highlighted the possibility of using the ships' communications bandwidth to send near-real time scientific data from ship to shore, further leveraging the technology that is already in use in the ships' high-tech vessel management systems.

Opportunities for International Participation and Collaboration

Leveraging the regular, repeated, global routes occupied by commercial vessels will provide an unprecedented opportunity for global in-situ data collection and global participation in ocean science. Commercial ships regularly transit regions far beyond the practical reach of research vessels. Inspired by the framework of the academic research fleet of vessels and building on their experience obtaining permissions to operate within countries' exclusive economic zones (EEZs), Science RoCS will greatly expand the fraction of the ocean that is accessible to oceanographic researchers and will provide universal access to the data.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers and Technologists

For these "integrated observing platforms" to be truly transformative and build global capacity, we will ensure that measurements are disseminated broadly and freely to all stakeholders, guided by four foundational principles of FAIR data—Findability, Accessibility, Interoperability, and Reusability (F.A.I.R.). Successful partnerships between shippers, sensor developers, equipment manufacturers, and data managers must ensure that the data are accessible without need for proprietary (often expensive) software. To build capacity among ocean scientists and stakeholders from coastal countries that do not have access to regular seagoing research operations, the "integrated observing platforms" will also include routes to address questions of regional interest.

We encourage anyone inspired by these efforts to reach out to Science RoCS. We welcome your input and participation!

Please contact, Kerry Strom, kstrom@whoi.edu, +1 530-289-3938. ***Science RoCS is the future and it's starting now, join us!***

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Ocean Sound Atlas

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ABSTRACT

Sound is fundamental to ocean ecosystems, yet the interplay of physical and biological sources and their relationships with ecological health and human activities is inherently complex and non-intuitive for visually oriented humans. Ocean Sound Atlas (OSA) will be a digital global ocean sound map. This interactive system will compile and integrate passive acoustic data by location of recording, for use by researchers, educators, policy makers, engineers, explorers, sound artists, and other stakeholder groups. The Ocean Decade is a unique opportunity to serve as the "hook" required to create and promote a central tool that will be widely used. OSA will harness increasingly exciting research potential into the ability to investigate key cross-cutting, multi-scale impactful questions.

Vision and Potential Transformative Impact

Sound is fundamental to ocean ecosystems, yet the interplay of physical and biological sources and their relationships with ecological health and human activities is inherently complex and non-intuitive for visually oriented humans. Ocean Sound Atlas (OSA) will be a digital global ocean sound map. This interactive system will compile and integrate passive acoustic data by location of recording, for use by researchers, educators, policy makers, engineers, explorers, sound artists, and other stakeholder groups.

OSA addresses obstacles to accessing and comparing acoustic data across projects. Simple to use and open source, OSA will serve as a repository for federal and federally funded project data, with additional contributions from academia, industry, and other sectors to achieve a more complete picture. Acoustic recording metadata varies widely across instrumentations and methodologies. Geographic information, however, is commonly collected. Location-based organization of sound recordings provides a realistic structure. Additionally, geographic visualizations enhance data accessibility and highlight gaps and opportunities.

The Ocean Decade is a unique opportunity to serve as the "hook" required to create and promote a central tool that will be widely used. OSA will harness increasingly exciting research potential into the ability to investigate key cross-cutting, multi-scale impactful questions.

FIGURE 1. Ocean Sound Atlas (OSA) will be a digital global ocean sound map.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The time is right for the OSA. Bodies from different countries have made steps towards recording and mapping ocean sound. The aim of this project is to pull these bodies and sound collection networks together, to help standardize and quality control information collected, and to use cutting-edge mapping software to display the data in a form that is valuable for a wide range of sectors.

Existing sources include NOAA's SoundMap program as well as sources belonging to other U.S. government agencies such as BOEM and the U.S. Navy, and foreign agencies. OSA would integrate with the National Ocean Mapping,. Exploration, and Characterization (NOMEC) Council, and multiple inter-agency working groups (e.g., Integrated Ocean and Coastal Mapping; Ocean Exploration and Characterization), as well as non-acoustic ocean mapping initiatives such as OceanReports. Partnerships will include the acoustic research community, marine conservation community, small business, citizen science, industry (oil and gas, shipping, technology developers), and Indigenous communities.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Ocean sound has obvious links to physical/ biological oceanography, yet mapping and using ocean sound data incorporates a wide range of disciplines and sectors. Sensor development involves physicists, acousticians, engineers and communications technologists. Mapping and analysis involves computer scientists, geospatial analysts, statisticians, and geographers. Graphic designers, social scientists and communications experts could ensure that the OSA is easily understood, intuitive, and is in a format that can be used by multiple stakeholders. The sounds themselves would be used by researchers, regulators, and other marine stakeholders, musicians, artists, educators, radio broadcasters, and podcasters.

Opportunities for International Participation and Collaboration

Numerous international projects would feed into or partner with the OSA such as the International Quiet Ocean Experiment; Discovery of Sound in the Sea; MERIDIAN Ocean Soundscape Atlas (Canada); Pandemic Silence Project; Native Land; and the World Forum for Acoustic Ecology. International treaty bodies and projects with interest or focus on underwater sound include: United Nations Convention on the Law of the Sea (UNCLOS); United Nations Environment Programme (UNEP); International Whaling Commission; International Maritime Organization (IMO); ACCOBAMS and ASCOBANS agreements of the Bonn Convention; Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Antarctic Treaty; and The International Convention for the Prevention of Pollution from Ships (MARPOL). International bodies have called for the study, assessment and management underwater sound, including the United Nations (e.g., para. 107 in Res. 61/222; para. 120 in Res. 62/215; Res. 71/257).

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Ocean sound, especially anthropogenic noise impacts on marine life, is an international issue, but collecting and integrating data can be technologically difficult and interpreting sound requires expertise. OSA will provide internationally accessible information, including resources to groups and regions without strong acoustics programs and technology. The OSA will supply data to educators of various levels, already in a more accessible format. Likewise, sounds will be available to the media. The available data and accessible map will allow the OSA to connect across governmental and disciplinary boundaries, to reach a large audience and inspire curiosity, inquiry, and action on underwater sound.

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COBRA: A Research Accelerator for the Crustal Ocean Biosphere

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ABSTRACT

The deep seafloor covers two-thirds of Earth's surface area, but our understanding of the ecosystems and resources found in the deep ocean, as well as the ability of deep-sea ecosystems to withstand human perturbation, is limited. These deep-sea habitats demand urgent study as there are emergent human uses in the form of deep-sea mining and carbon sequestration that will fundamentally alter physical, chemical, and biological conditions that took millions of years to establish. We propose the international network COBRA, a research accelerator for the crustal ocean biosphere. COBRA will bring together diverse stakeholders and experts, including interdisciplinary academic and government scientists, private institutions, policy makers, data systems engineers, industry experts, and others to coordinate efforts that generate new knowledge and inform decision making about activities that could affect the deep ocean and, by extension, all of society. We will also train the next generation of leaders in ocean exploration, science, and policy through an innovative virtual program to carry this effort into future generations of ocean and earth science research. COBRA will inform policies relating to emergent industrial uses of the deep ocean, decrease the likelihood of serious harm to the environment, and maintain ecosystem services for the benefit of society.

Vision and Potential Transformative Impact

The potential far-reaching impacts of mining and carbon sequestration on deep-ocean ecosystems underscores the urgent need to understand the crustal ocean biosphere in ways that will immediately enable smart resource management. Deep-sea mining trials are already underway, and draft regulations for seabed mining code are taking shape. Likewise, trials of subseafloor carbon sequestration have begun. Both activities have the potential to dwarf other human impacts in the deep sea, yet the science to inform and evaluate the impacts of these new industries is lacking. A grand challenge for the international scientific community is to determine the ecosystem structure and function of the crustal ocean biosphere and its resilience or vulnerability to human disruption. Our vision is to accelerate this effort in order to inform sustainable management of the deep ocean and subseafloor, especially related to the emergent human activities of deep-sea mining and carbon sequestration. We will achieve this through a "network-of-networks" approach that facilitates collaborative ocean exploration expeditions and observations in ways that identify mutual benefits to multiple stakeholders. In addition to the challenges of the Ocean Decade, outcomes will also be relevant to achieving objectives of the US National Strategy for Mapping, Exploring and Characterizing the U.S. EEZ.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

We will bring together an international mix of interdisciplinary academic and government scientists, private institutions, policy makers, engineers, and other stakeholders to coordinate efforts and to achieve objectives of mutual benefit that catalyze new knowledge and inform decision making. Given the focus well beyond science, including ocean legal and societal issues, this effort will include engagement with and entrainment of experts in a variety of sectors outside of traditional ocean sciences, including resource and environmental economists, industrial mining and carbon sequestration specialists, manufacturers, political and social scientists, lawyers, historians, and data systems engineers.

Opportunities for International Participation and Collaboration

This program will enable international partner networks and organizations to forge new linkages, strengthened by a student and young investigator exchange program and expedition leadership training program. Potential partnerships will include InterRidge (global, focus on mid-ocean ridge environments), the Excellence Cluster Ocean Floor at MARUM (Germany, focus on seafloor processes), the K.G. Jebsen Centre for Deep Sea Research (Norway, focus on the deep sea and its potential resources), the Science for Clean Energy consortium (EU, focus on subsurface energy industry), Ocean Networks Canada (ocean observation), and the Deep-Ocean Stewardship Initiative (global, ecosystem-based management of resource use in the deep sea).

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

We will combat the continued inequity faced by historically excluded groups in oceanographic research and the persistence of colonialist mindsets that do not meaningfully engage local communities and stakeholders. We will train a new generation of diverse and globally distributed leaders in ocean exploration and characterization through an innovative virtual training program that leverages public–private telepresence assets and that establishes and elevates best practices for promoting diverse, equitable, and inclusive collaboration. Such connections will enable capacity-building and skills training to expand the workforce in ocean research for sustainable development.

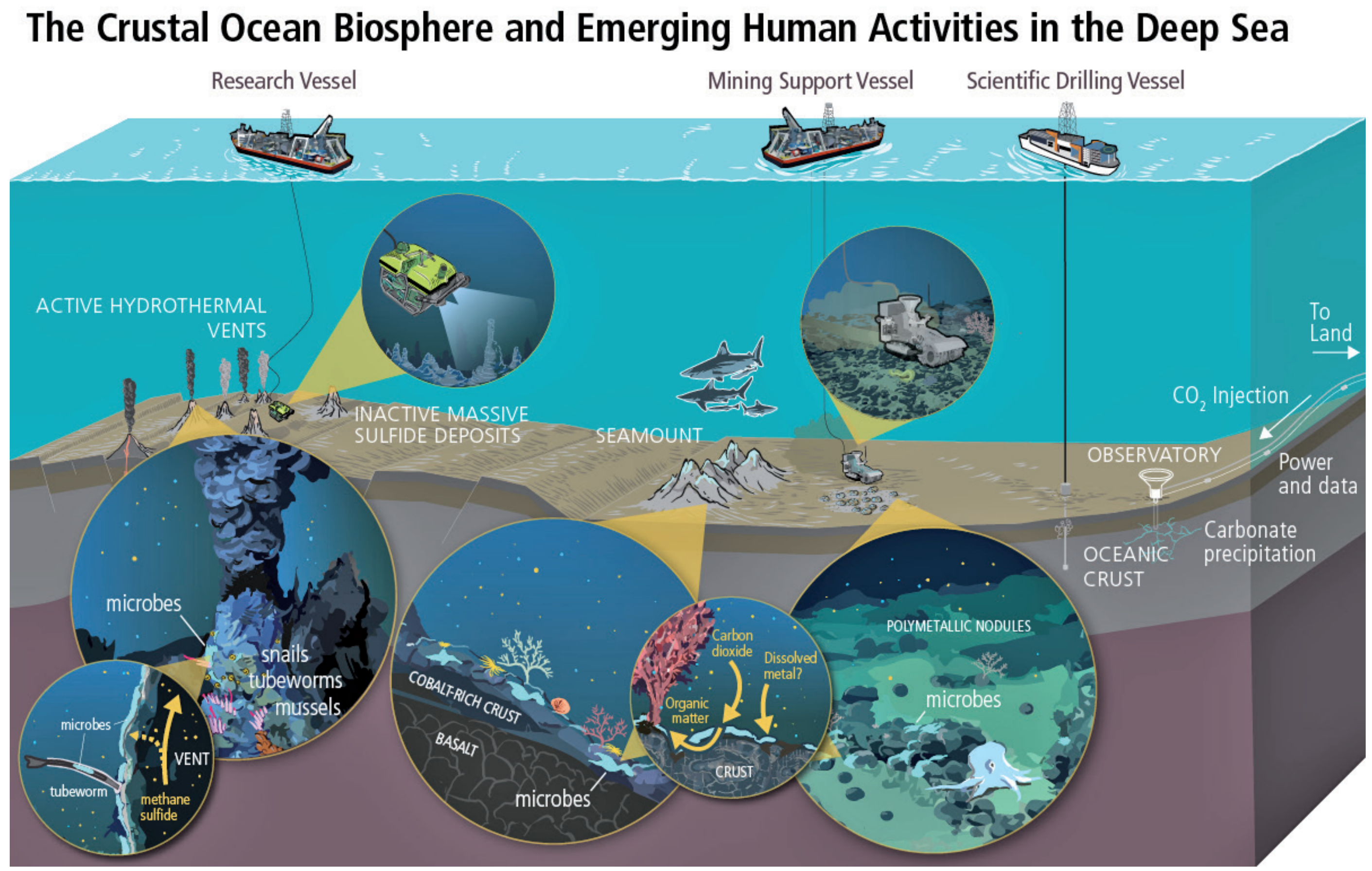

FIGURE 1. Schematic of the crustal ocean biosphere, emphasizing emergent human activities in these habitats, such as 2 deep-sea mining and carbon capture and sequestration. From Orcutt, B.N., D'Angelo, T., Jungbluth, S.P., Huber, J.A., & Sylvan, J.B. 2020. Microbial life in oceanic crust. OSF Preprints. https://osf.io/2wxe6/.

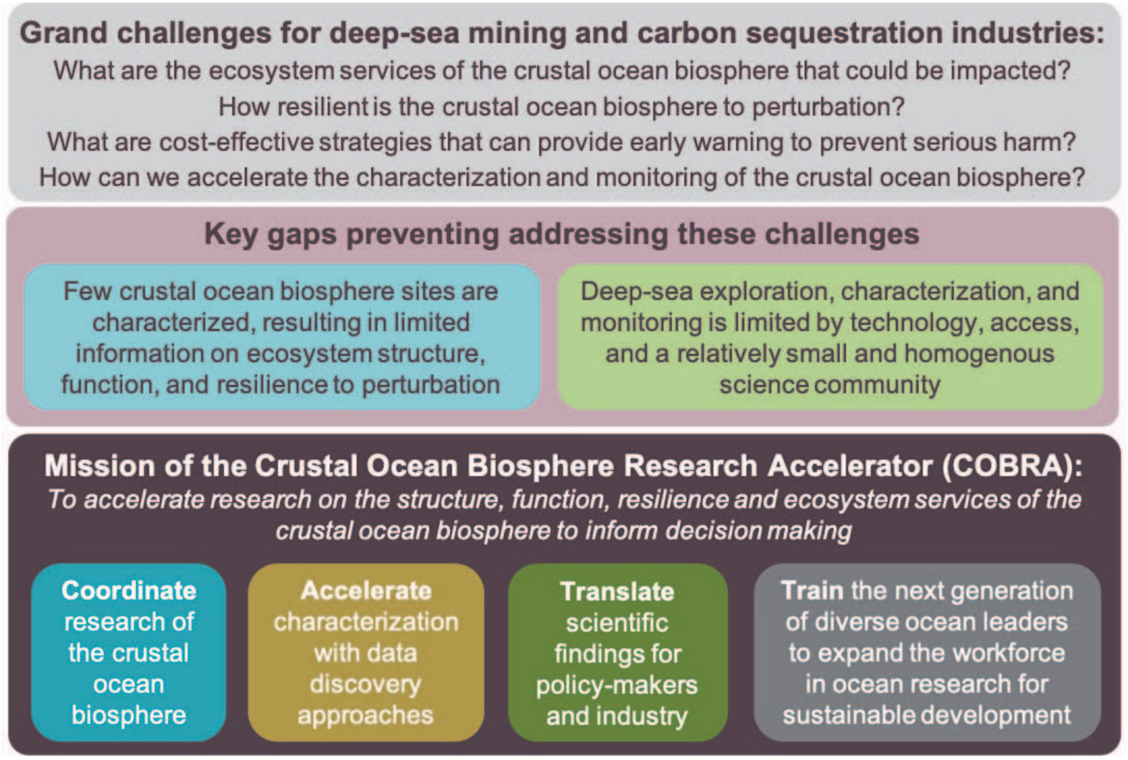

FIGURE 2. Challenges and mission of COBRA.

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Ocean Arc: An Ocean Shot for the Arctic

Heather M. Tabisola[1,2], **Calvin C. Mordy**[1,2], **Brian Skerry**[3], and **Christopher Meinig**[2]

[1]University of Washington Cooperative Institute for Climate, Ocean & Ecosystem Studies; [2]NOAA PMEL; [3]Brian Skerry Ltd.

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ABSTRACT

Photography can be a powerful instrument for change. Combining scientific research, new imaging technologies equipped with Artificial Intelligence, and underwater photography, we'll share near- to real-time changes of biodiversity in the Arctic and highlight these rapidly changing and unique environments. Through this project we will continually develop new ways of creating images and stories that both celebrate the sea yet also highlight environmental stress.

Scientists often speak of a "new Arctic" to describe the region's rapidly changing landscape and marine systems. Temperatures are higher than before, sea ice is dwindling, and many experts believe the far north is quickly transforming into something unrecognizable.

A new Arctic will be warmer, rainier, and substantially less frozen. Animals that used to be common may disappear, while new species may move in to take their place. Opportunities for hunting and fishing by sea ice are declining. And shipping in the region is already significantly increasing as the ice disappears. With this, planning for natural and human-made disasters is an increasingly daunting task.

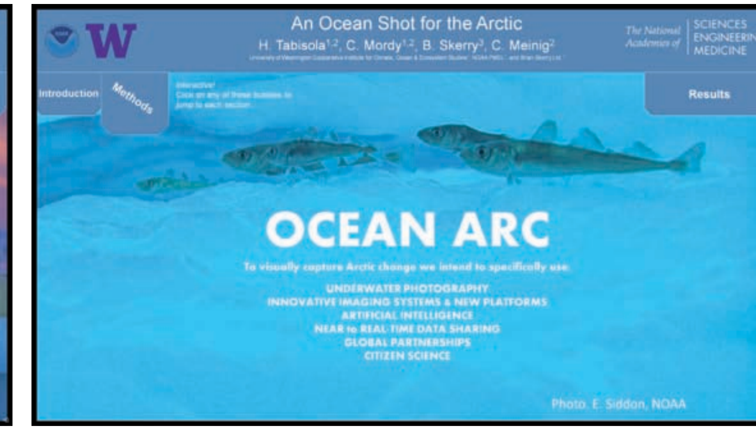
We want to take an Ocean-Shot and visually capture this change in a way that has never been done before. We want to transform the way in which science can be conducted.

Vision and Potential Transformative Impact

Arctic marine ecosystems are undergoing rapid change with reductions in ice and immense shifts in biodiversity. Yet these changes have been difficult to document due to the remote and harsh arctic environment that includes seasonal sea ice. Our vision is to deploy new and innovative imaging systems to visually map changes in arctic marine ecosystems including plankton, fish, whales, under-ice algal communities, and the benthos from various platforms and in all seasons. These systems will be combined with artificial intelligence (AI) that will identify plants and animals in real time, and provide an index of species diversity (i.e., number and abundance of different species) across the arctic. AI will also be used for ice avoidance and navigation of autonomous vehicles. Much of this data will be available in near-real time with open-source images and data, and this story will be shared primarily through underwater photography. This project is not only transformative for documenting changes in arctic marine ecosystems, but new inexpensive imaging systems that are currently in development will be available to coastal communities from pole-to-pole, and these images and data will be consolidated in an ocean viewer for mapping and disseminating changes in the global ocean.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

This program will be initiated at the University of Washington (UW) and NOAA's Pacific Marine Environmental Laboratory (PMEL). PMEL has a long history of developing tools to observe the global ocean including the global tsunami forecasting system, the Global Tropical Moored Buoy Array Program, a multi-national effort to provide data in real time for climate research and forecasting (e.g., El Niño), and global monitoring of Ocean Acidification. The Innovative Technology for Arctic Exploration program at UW and PMEL (Mordy co-PI, Tabisola coordinator) provides innovative thinking and high-risk development projects in the U.S. Arctic. In five years, the program has worked to create new platforms, imaging systems and aircraft deployable assets to observe a changing arctic when ship-based research is extremely limited. The programs have exemplary credentials with private–public partnerships including Saildrone Inc., McLane Laboratories, and Google AI. This proposal will foster a new partnership with award-winning National Geographic photojournalist Brian Skerry.



Scientific/Technological Sectors Engaged Outside of Traditional Ocean

Our program has expertise in transitioning traditional technology for marine applications. The program will be working with several companies to further develop traditional microscopic and time-lapse imaging systems, and will collaborate with several software companies for implementation of AI (e.g., Google AI is being used for identification of zooplankton). Diversity indices that are developed for the marine environment will be used to track climate impacts alongside similar indices used for terrestrial ecosystems in Alaska. Skerry will use images and photography in powerful presentations that blend award-winning imagery and thrilling wildlife encounters for a powerful call to action.

Opportunities for International Participation and Collaboration

We welcome the opportunity for international participation and collaboration to strengthen and enhance the project. From inception, the ITAE program has led teams of 5 to >50 individuals and understands the value each person brings to a project. With that, it would be our intention, as needed, to leverage current scientific partnerships within the university, NOAA, and NSF including the Interagency Arctic Research Policy Committee. And at the core vision of this project would be to partner and engage with various local native Alaska communities, including artists who are witnessing the impacts first hand and may wish to participate.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

These imaging and AI systems will be provided to global collaborators through PMEL's network of partners and enable an expansive view of changing ecosystems. We envision a network of observing partners that will include citizen scientists, and students (K–12 to university) from international academic institutions, all of whom will be connected through maps displaying changes in biodiversity. More than just data and maps, the imagery and photography will be a powerful tool for visual storytelling as demonstrated in so much of Mr. Skerry's photojournalism and filming.

Funding: This project is partially funded by the Innovative Technology for Arctic Exploration program at NOAA Research, Pacific Marine Environmental Lab, Seattle, WA.

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The 4-Site Pacific Transect Collaborative (4-Site)

Judith Lemus[1], Neil Davies[2], Joachim Claudet[3], Annaig Leguen[2], Alexander Mawyer[4], Frank Murphy[5], Alex Wegmann[6], and **Nicholas Wolff[6]**

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ABSTRACT

The vastness of the Pacific Ocean, and the geographic isolation of its island nations, sets the stage for critical disconnects between the drivers and causes of climate change and their local impacts in Pacific Island communities. Pacific Islands, as elsewhere, face persistent local crises at the nexus of natural and human systems that have altered the way we interact with our environments, raising challenging questions about how to sustain the well-being of our communities, and their associated coral reef ecosystems. These ecosystems and communities that rely on them are "canaries in the coal mine" for climate change and biodiversity loss. At the same time, the scientific, technological, indigenous, and social knowledge systems that could contribute to sustainable futures are often siloed in disciplinary as well as political contexts. It is in this arena that the 4-Site Pacific Transect Collaborative seeks to work. The big question we ask is, "What knowledge infrastructure is needed to equitably and democratically support Pacific Islands societies in achieving Sustainable Development Goals and promote the resilience of coral reef social-ecological systems"?

Vision and Potential Transformative Impact

The 4-Site Collaborative brings together partners from four well-established, respected research institutions across national borders in the Pacific to enhance adaptive capacity and accelerate action-oriented sciences that will support Pacific Islands societies in achieving Sustainable Development Goals and the resilient well-being of coastal social-ecological systems. The project applies a large-scale, collaborative, transect approach that leverages the islands of Tetiaroa, Moorea, Palmyra, and Oahu as model systems for contributing to the intelligence infrastructure needed for island communities to navigate towards sustainable futures.

The persistent "crisis of the now" in Pacific Island communities has altered the way Islanders interact with their environments and raised challenging questions about governing, managing, and sustaining the well-being of regional communities. Coral reefs are especially threatened by a variety of direct and indirect anthropogenic stressors, including increased ocean temperatures and acidification. To combat these existential threats, it is critical to: identify the factors that predict resilient social-ecological systems; integrate and amplify these factors in the design of effective interventions; and implement them through robust management plans and policy frameworks. A place-based model system that integrates local to regional scale dynamics can enable communities to make better conservation decisions quicker and with far less scientific investment or local data gathering.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The collaborative is anchored at research hubs on Oahu (University of Hawai'i), Palmyra (The Nature Conservancy), Moorea (GUMP, CRIOBE-CNRS-EPHE), and Tetiaroa (Tetiaroa Society). We propose a model system approach focused on islands representative of regional diversity, ranging from small private atolls to large heavily populated islands, and spanning a transect across the tropical latitudes currently optimal for coral reefs (Figure 1). 4-Site members are already intimately connected to local communities and decision makers that manage coral ecosystems and desire sustainable futures. For example, HIMB partners with six community organizations in managing biocultural restoration of the He'eia National Estuary Research Reserve; CRIOBE has partnered with local communities on Tahiti to establish a large-scale network of rahuis, a traditional form of community-based management; and Tetiaroa Society is partnering with traditional land and sea tenure holders in Arue, Tahiti around sustainable use and marine stewardship issues in the wake of COVID-19.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Oceania hosts significant research capacity supported by governments, universities, NGOs, and private foundations, fostering richly situated social and ecological knowledge to support management and policy with an eye on sustainable development goals. Leveraging our collective expertise to critically examine social innovations such as spatial planning and implement culturally-grounded data, knowledge, values, and perspectives is critical to equitably achieve goals at nested-scales of social-ecological organization. 4-Site will focus on community-driven pathways to develop science-based interventions through management plans and policy frameworks that include Indigenous and local knowledge to ensure they are context specific and culturally aligned.

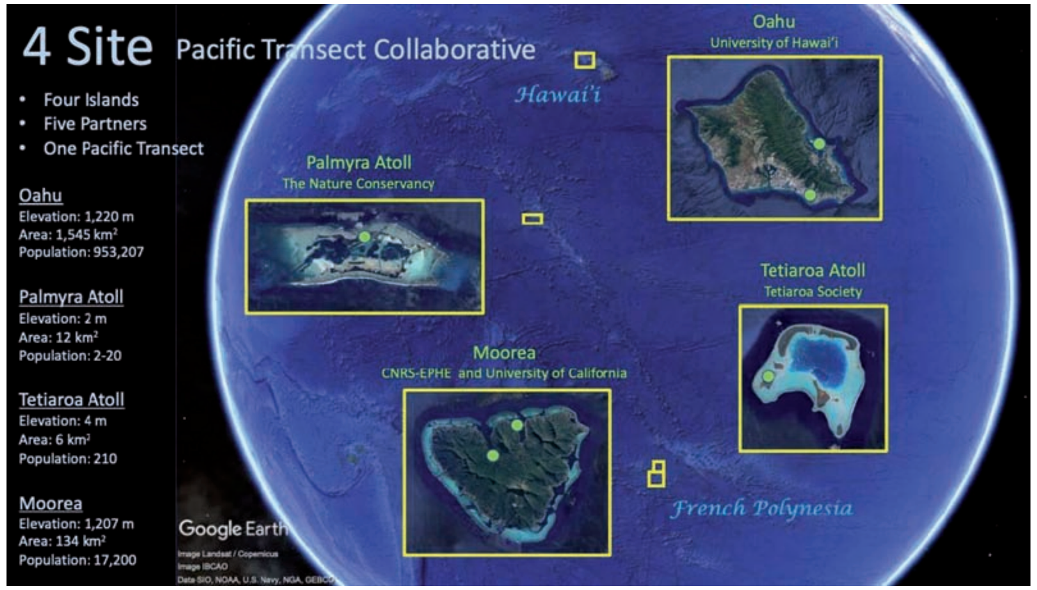

FIGURE 1. The 4-Site geographic model.

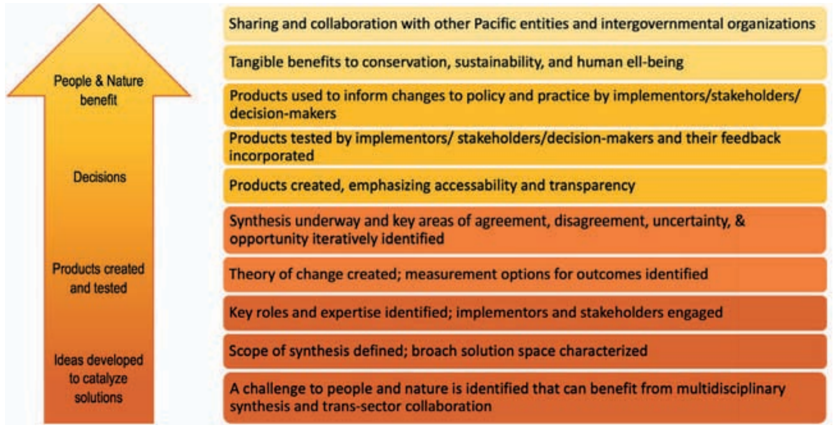

FIGURE 2. The 4-Site impact ladder.

Opportunities for International Participation and Collaboration

4-Site proposes a series of science-community dialogues and workshops with island nation interested parties to collaboratively:

- Characterize functional attributes of nested social-ecological system components, incorporating multidisciplinary data;
- Model and quantify relationships between functional attributes under historic and current conditions;
- Map how data and knowledge are utilized in different contexts to conserve and sustainably use natural resources;
- Predict trajectories of nature's contribution to human well-being under various policy-driven scenarios and environmental conditions using the Island Digital Ecosystem Avatar Consortium's predictive modeling approach;
- Engage and Support Indigenous peoples and local communities with templates for island sustainability plans using community-driven data stewardship and equitable dialogues.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Addressing foundational questions about resilience in coastal social-ecological systems requires communities to process complex and uncertain dynamics in order to make multi-dimensional decisions. Islands represent efficacious natural laboratories of integral relations between human, environmental, and ecological well-being over millennia. Leveraging place-based scientific model systems, calibrated along a transect, can help local, regional, and coastal communities across the globe build capacity in conservation decision making. By including Pacific Island college students in our synthesis workshops we will extend this impact by providing an opportunity for young scientists to learn through experience and be mentored by community leaders and environmental professionals.

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FathomNet: An Open, Underwater Image Repository for Automated Detection and Classification of Midwater and Benthic Objects

Kakani Katija, **Brian Schlining**, **Lonny Lundsten**, **Kevin Barnard**, and **Giovanna Sainz**, Monterey Bay Aquarium Research Institute; **Océane Boulais**, MIT Media Lab; **Benjamin Woodward**, CVision AI; **Katy Croff Bell**, Ocean Discovery League

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ABSTRACT

Ocean-going platforms and instruments are integrating cameras for observation and navigation, producing a deluge of visual data. The volume of this data collection can rapidly outpace researchers' abilities to process and analyze them. Recent advances in artificial intelligence enable fast, sophisticated analysis of visual data, but have had limited success in the oceanographic world due to lack of dataset standardization, sparse annotation tools, and insufficient formatting and aggregation of existing, expertly curated imagery for use by data scientists. To address this need, we are building FathomNet, a public platform that makes use of existing (and future), expertly curated data to know what is in the ocean and where it is for effective and responsible marine stewardship. This platform is modeled after popular terrestrial datasets (e.g., ImageNet, COCO) that enabled rapid advances in automated visual analysis. FathomNet seeks to engage a wide audience, from the general public to subject-matter experts, to further augment, contribute to, and utilize the training data set. FathomNet will accelerate development of novel algorithms to automate the analysis of underwater visual data, thereby enabling scientists, explorers, policymakers, storytellers, and the public, to learn, understand, and care more about our ocean and its inhabitants.

Vision and Potential Transformative Impact

This project will rapidly advance the ways in which we use image data to observe and monitor our oceans on a global scale. This platform is modeled after Stanford's ImageNet and Microsoft's COCO that, along with other datasets, enabled rapid advances in automated visual analysis in terrestrial environments—FathomNet will be the ocean equivalent (Figure 1). Starting with MBARI's 30-year, expertly curated, underwater video database that aggregates and organizes ROV footage, FathomNet has been built to incorporate existing datasets from other contributors (e.g., NOAA-OER, National Geographic Society) and elsewhere. The compilation of these data will enable automated classification of targets throughout the global ocean, and drive ocean exploration and discovery in new and challenging directions. FathomNet has the potential to transform and enable how the ocean community annotates past, present, and future data, revolutionize video data management and accessibility, and enable adaptive sampling and unstructured discovery throughout the depths of the ocean.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The FathomNet project has received financial support from the National Geographic Society, NOAA's Office of Exploration and Research, as well as institutional support from MBARI, the David and Lucile Packard Foundation, and the MIT Media Lab. The FathomNet database has initially leveraged MBARI's 30 year, expertly curated, underwater video database that aggregates and organizes ROV footage, and FathomNet has been built to incorporate other existing datasets and infrastructure from our partners, collaborators, and contributors (e.g., National Geographic Society, NOAA, etc.). As an open, public database, we have already engaged with for-profit entities (e.g., CVision AI, SQUIDLE+) that will be contributing to and utilizing the data contained within FathomNet. The FathomNet database has already been implemented, and the roll-out of the web interface (Figure 2) is anticipated in early 2021. Algorithms trained using FathomNet, and later deployed on imagery and video, could generate data that could be contributed to IOOS, WoRMS, GBIF, BCO-DMO, and iDigBio.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

As the goal of FathomNet is to provide a platform that can engage partners outside of the ocean science community to tackle pressing problems in technology development and artificial intelligence, we are directly seeking non-traditional institutions and partners. In addition to our academic partners (e.g., MBARI, Caltech, MIT Media Lab), we have engaged contributors traditionally outside of ocean sciences that include government agencies (e.g., NOAA-OER), for-profit (e.g., CVision AI), and non-profit (e.g., National Geographic Society, Monterey Bay Aquarium, Ocean Discovery League) organizations. Through these connections and ongoing collaborations, we expect involvement with numerous scientific and technological sectors outside of the traditional ocean sciences community.

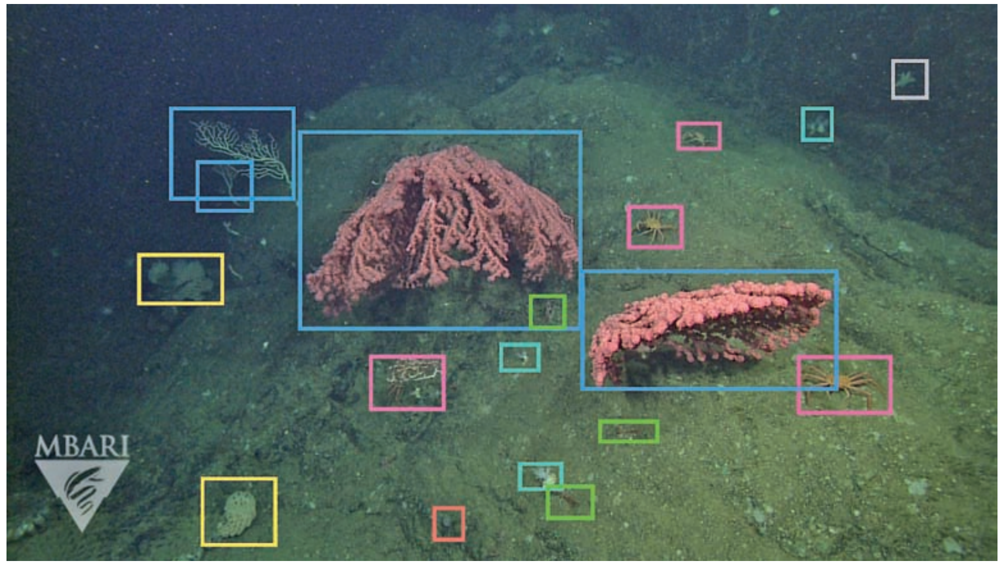

FIGURE 1. Example image revealing annotations and localizations of benthic fauna in Monterey Bay National Marine Sanctuary.

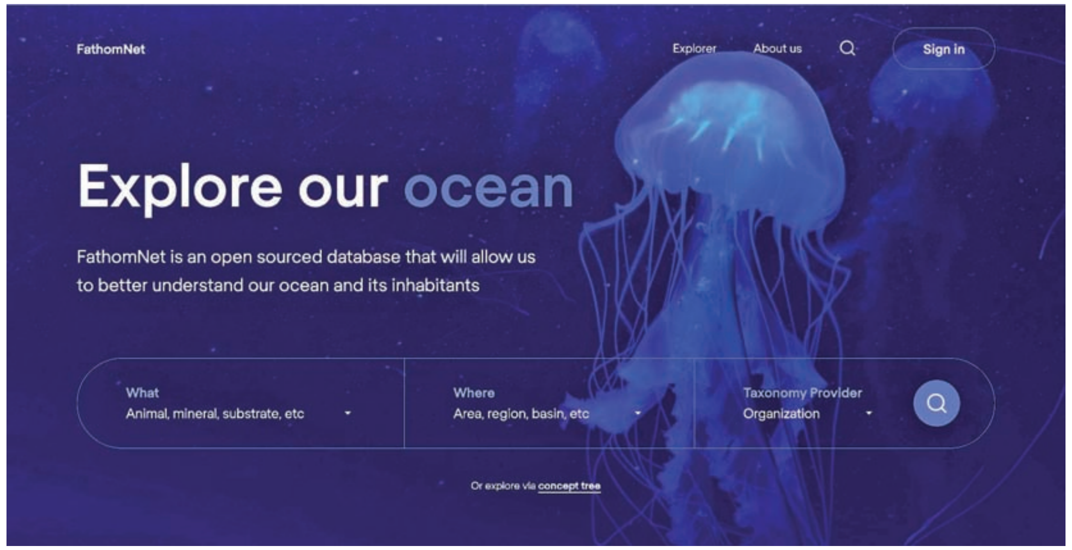

FIGURE 2. Homepage for FathomNet at http://www.fathomnet.org/.

Opportunities for International Participation and Collaboration

FathomNet is a database built on FAIR data principles, and incorporates image data independent of the platform used to collect it. As such, we anticipate contributions from the general public to subject-matter experts. The goal is to create an image database of underwater concepts (e.g., animals, geologic features, etc.) that is globally distributed and provides vital data for machine learning algorithm development. In addition to the global reach of our data contributors (e.g., National Geographic Society), we are reaching out to researchers worldwide to contribute their data and expertise to FathomNet. Anyone, anywhere, can ultimately use FathomNet.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

FathomNet aims to engage people of all levels of expertise throughout the world. To do this, we are planning to launch a community outreach effort that engages members of the public and subject-matter experts to contribute to, augment, and verify the data within FathomNet via its dedicated website interface, application, and social media. These tools will also enable communities that have been historically excluded from exploration to contribute to and access this extensive global database. While additional funding is required to build out these features, a relatively small investment to enable community-building features will contribute significantly to FathomNet's success.

Funding for this work provided by National Science Foundation (GEO-OCE-OTIC), EAGER–Integrating machine learning on autonomous platforms for target-tracking operations using stereo imagery, #1812535 to KK; NOAA/MIT Sea Grant, FathomNet: Toward an open underwater image training set, NA18OAR417010 to KK and KCB; and David and Lucile Packard Foundation to KK.

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Auscultating the Oceans: Developing a Marine Stethoscope

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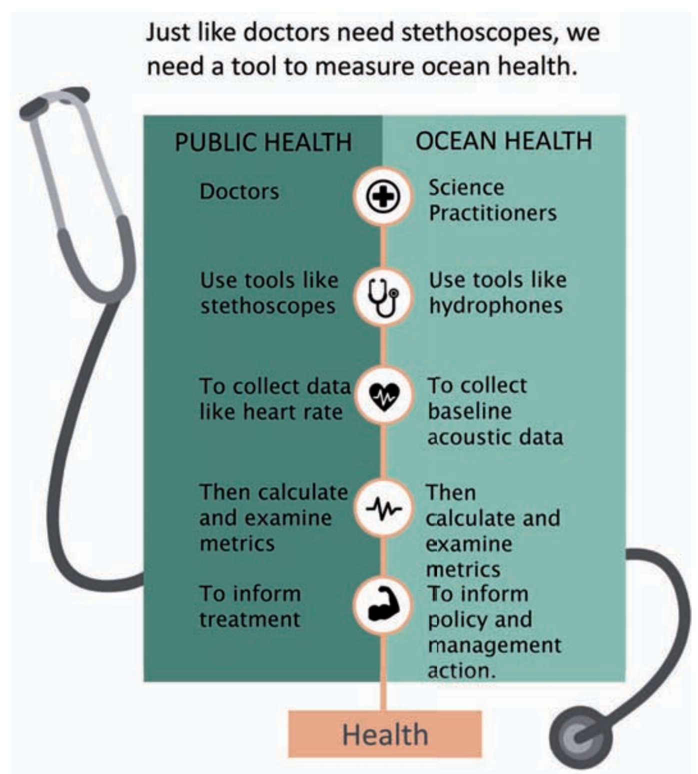
ABSTRACT

In the public health sector, nurses and doctors use tools like stethoscopes to assess health based on sounds. Much like the human body, the ocean's interior is awash with sounds that contain rich information relating to the current state of processes and life within. Based on these ideas, it is hypothesized that sound information can be used in a similar way to assess ocean health. This Ocean-Shot Concept seeks to build this capability through the establishment of objective baselines for regional acoustic environments, along with skilled practitioners that can interpret what they hear. This concept will be transformative in that patterns of natural and anthropogenic sound can be monitored and assessed to enable diagnostic capabilities. This new capability will provide a data-informed basis for recommending policy and management of regional seas using soundscape data. It also seeks to attract the next generation of ocean scientists through outreach and early engagement through development of a toy marine stethoscope akin to what is found in a child's medical kit.

Vision and Potential Transformative Impact

Sound carries with it a rich amount of information pertaining to both sources and the environment. With the efficiency at which it travels in water, sound provides a vantage point for peering into vast swatches of our ocean's interior. Using these traits, envisioned is a capacity for listening to the full range of consonant and cacophonous sounds in the ocean and objectively assessing its current and future state. The *marine stethoscope* concept is inspired by recent advances, including the use of machine learning, to aid listening to, and labeling, heart and lung sounds as has been done starting with the invention of the stethoscope in 1816. The vision will be enabled by technology, information processing capabilities, and standards for characterizing the undersea acoustic environment at temporal and spatial scales relevant to human and marine life. These will be used to establish objective baselines for acoustic environments and provide activity-based information in and across regions. It will be transformative in that these newly identified patterns of natural and anthropogenic sound can be monitored and assessed to enable diagnostic capabilities. This new capability will provide a data-informed basis for recommending policy and management of anthropogenic sound in the context of extant regional soundscapes.



Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

A recent inventory of federally funded passive acoustic monitoring assets included over 120 entries with support coming from eight agencies plus the National Oceanographic Partnership Program (NOPP), and the National Fish and Wildlife Foundation, Packard Foundation, Greenland Institute of Natural Resources, and Korea Polar Research Institute. The International Quiet Ocean Experiment (IQOE) has documented a mix of cabled, fixed-autonomous, and mobile-autonomous observation assets, with approximately 50 having acoustic capabilities around the globe. The Comprehensive Test Ban Treaty Organization (CTBTO) hydroacoustic stations provides a good example for low-frequency sound. The Exploration and Production Sound and Marine Life Joint Industry Program (JIP) can provide direct connectivity to the petroleum industry. Communication, coordination, and collaboration among entities to agree upon metrics, measurement, and data accessibility practices and sustainment approaches will bring the vision to realization. This includes developing new technology solutions as required for the benefit of the community. The National strategy for Ocean Mapping, Exploring, and Characterizing (NOMEC) the U.S. Exclusive Economic Zone provides another implementation path.

Example of a reconfigurable hydrophone mooring for ambient sound measurements.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Ocean Acoustics is highly intertwined with both the physical and biological aspects of the ocean that define the field of oceanography, yet it is often underrepresented in the ocean sciences community. This topic will integrate acoustics into the broader ocean sciences community as well as engage expertise in fields such as Machine Learning, Artificial Intelligence, Pattern Recognition, Signal Processing, Information Theory, Statistics, Geospatial Analysis, and others. Drawing on people's affinity for music, biology, computer science, and exploration, a robust and inclusive education/outreach program will encourage development of a multi-disciplinary community with the knowledge and skillset required to understand the ocean through sound.

Opportunities for International Participation and Collaboration

Sound is an Essential Ocean Variable (EOV) in the Global Ocean Observation System. IQOE has endorsed projects around the globe that include monitoring and modeling sound in five different seas around the globe. Listening to the Deep Ocean Environment (Lido)—listentothedeep.com—hosted at the Technical University of Catalonia provides a real-time interface for observatory data. A "Joint Action" on "Underwater Noise in the Marine Environment" is being developed by the Joint Programming Initiative—Healthy and Productive Seas and Oceans (JPI Oceans), an EU intergovernmental platform. In October 2021, the European Multidisciplinary Seafloor and water column Observatory (EMSO) is hosting a conference on monitoring underwater sound for environmental purposes.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

This concept promotes sound as a defining characteristic of the ocean environment that is intertwined with both the physical and biological aspects of oceanography. It reveals a hidden demand signal for needed training in acoustics alongside the physical, biological, mathematical, and engineering sciences required to support the ocean sector. Making connections with music, exploration, medicine, and other fields can further encourage development of education/outreach programs to build a diverse community. Development of an inexpensive junior ocean stethoscope (akin to what's found in a children's medical kit) could engage school children and aid outreach.

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The U.S. Ocean Biocode

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ABSTRACT

Biodiversity is the engine of ocean ecosystems and economies. Efficiently characterizing it, rapidly at high resolution, is the frontier for understanding global change and management. The biggest impediment to breaching that frontier is inadequate DNA reference libraries, which can currently identify <25% of animal species in environmental profiles. Over the course of the decade, we will build from our existing global network of museums, universities, federal agencies, and the private sector in a broad collaboration to produce the Ocean Biocode, a well-sampled, voucher-based, open-access reference library of U.S. marine species that will eliminate "dark taxa" (no name or phylogenetic position) from U.S. waters and support a new era in high-resolution oceanography and environmental science founded on accurate environmental DNA sampling. We need not sequence every species; a strategic, empirically guided inventory will fill key gaps by focusing BioBlitz efforts at one focal site in each marine ecoregion of the U.S. EEZ, targeting taxa missing from regional libraries, coupled with genome skimming, to create reference libraries of whole mtDNA and nuclear ribosomal cluster. This Ocean Biocode moves beyond the barcode to allow design of targeted probes for non-amplicon species detection, yielding species-level information to stakeholders and enabling future technologies.

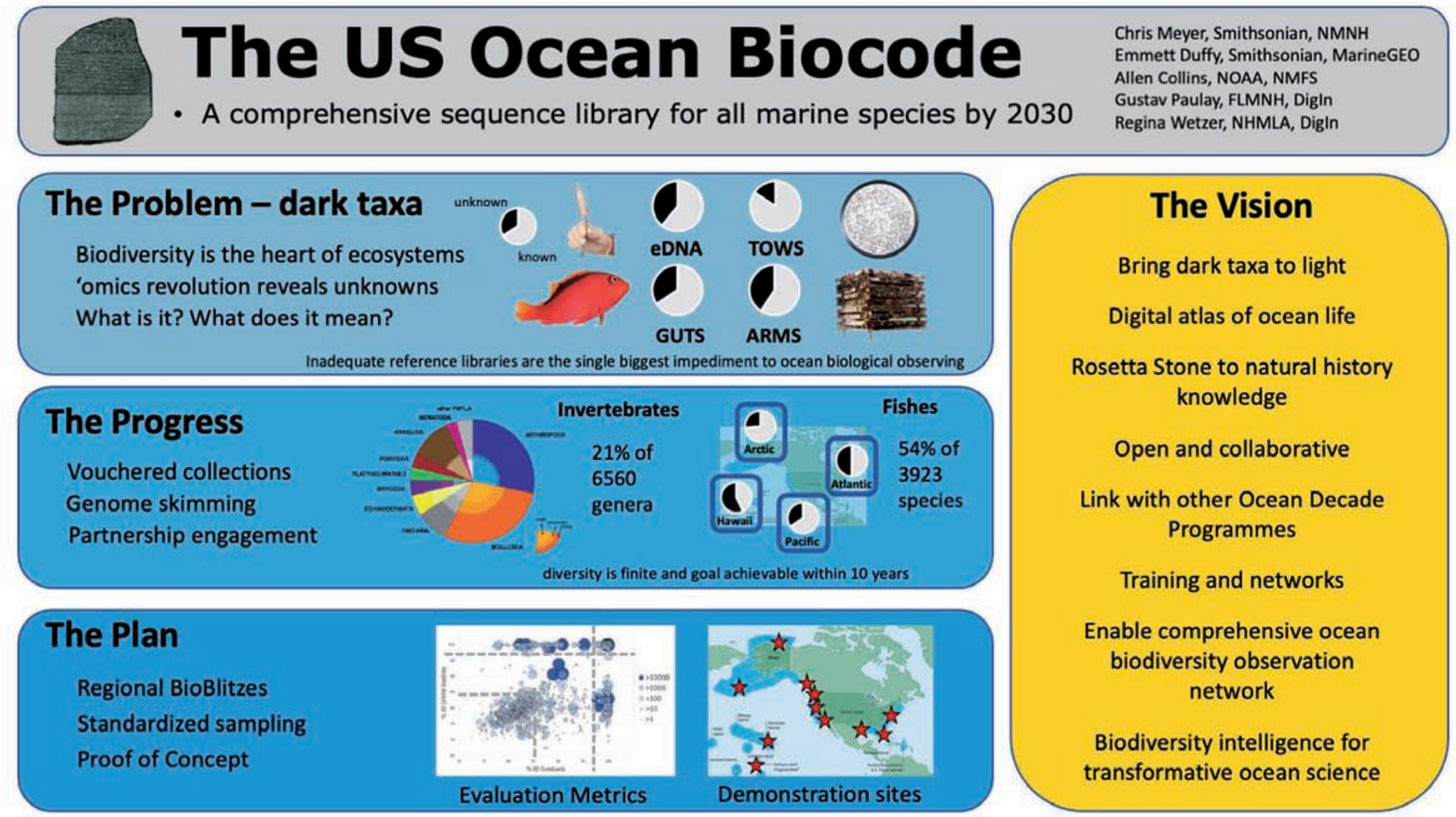
Vision and Potential Transformative Impact

Knowing an organism's identity and position on the tree of life is fundamental to everything in biology. Yet, for much of the ocean's life, we have neither. Now, for the first time, we have the technical capacity to overcome this challenge using DNA, the foundational layer of biodiversity. Transformative sequence-based approaches to sampling (e.g., eDNA) allow censusing of marine communities with unprecedented scale and resolution using automated environmental samplers and AUVs. Miniaturized, onboard sequencing technologies are reducing return times of critical biological data to stakeholders, fostering impactful decisions in near-real time. However, unlocking the capacity of 'omics-enabled censusing depends critically on linking sequences to taxon identities. Without this biocode, DNA data are merely sequences of letters.

Our proposal will transform ocean intelligence by facilitating a complete, sequence-based inventory of marine biodiversity. Combining genome-skimming with vouchered specimens will substantially expand open-access digital tools for monitoring both living marine resources and threats (invasives, HABs). Lineage-specific probes can be developed to target genetic material resistant to environmental degradation. We will transform natural history museums into a new 21st century role as accountants of change, by adapting to archive snapshots of entire ecosystems and time capsules available to future technologies (future-omics).

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The Smithsonian Institution is well-positioned to lead this effort. As a leader among U.S. natural history collections, the National Museum of Natural History has the experience and expertise with marine collections, the institutional investment through the OceanDNA Initiative, and commitment of the leadership team to work with national partners and agencies. We have existing partnerships with federal agencies, particularly NOAA, BOEM, and USGS, within the marine space. The One World collection efforts to coordinate natural history museums with respect to taxonomic, regional, and personnel coverage provides a built-in coordination platform. We will also tap iDigIn partners, marine labs, Smithsonian's MarineGEO program, MBON, and LTER activities to engage new field work and existing collections to achieve the Ocean Biocode. We will build on tools developed by the SI-based Global Genome Initiative, and the SI co-led Global Genome Biodiversity Network (GGBN) to assure access, standards compliance, and metadata interoperability.



Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

All stakeholders concerned with marine organisms will benefit from the Ocean Biocode. DNA sequencing and 'omic-based detection are the future of biological monitoring, delivering capacity for novel scientific inquiry (e.g., trophic interactions, phenology, recruitment). The capacity to identify a species non-invasively, from derived products at any life stage, or as shed material opens doors to many innovative applications. A comprehensive reference library invites new technological development. NMNH's core mission to disseminate knowledge also uniquely poises us to connect people to their Ocean, and to create an understanding that our choices and behaviors impact ocean health and thus our own well-being.

Opportunities for International Participation and Collaboration

Documenting and understanding marine biodiversity is a global endeavor and the Ocean Biocode will convene partners accordingly. We fully expect international participation. We will build on our active collaborations with partners who can help advance this effort, including the GEO-BON Marine Biodiversity Observation Network; Smithsonian MarineGEO's network of partners; other Ocean-Shot proposals, Ocean 'Omics efforts; and through international ocean best practices and standards community engagement (e.g., OBIS, GBIF, WoRMS).

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

We are committed to inspiring the next generation of ocean stewards in the process of developing this national catalogue of ocean life. Through regional BioBlitz efforts and subsequent collections curation, laboratory analytical processes and informatics pipelines, we will provide enhanced, embedded, training opportunities to work side-by-side with mentors and experts at all stages of the program. We will have a particular emphasis to engage local stakeholders and under-represented communities in marine science in order to enrich and develop a cohort of marine role models for a more diversified marine community of scientists.

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Project Atuin

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ABSTRACT

Project Atuin brings together several bleeding edge technologies into a state-of-the-art, semi-autonomous research and ocean monitoring platform. Able to be deployed anywhere in the world and, in a future state, combined with a dedicated micro-satellite, the platform will be able to be accessed and given instructions from anywhere in the world. This modular science and protection platform will be deployed in partnership with local stakeholders and the data will be open to all and packaged into curriculum for all levels.

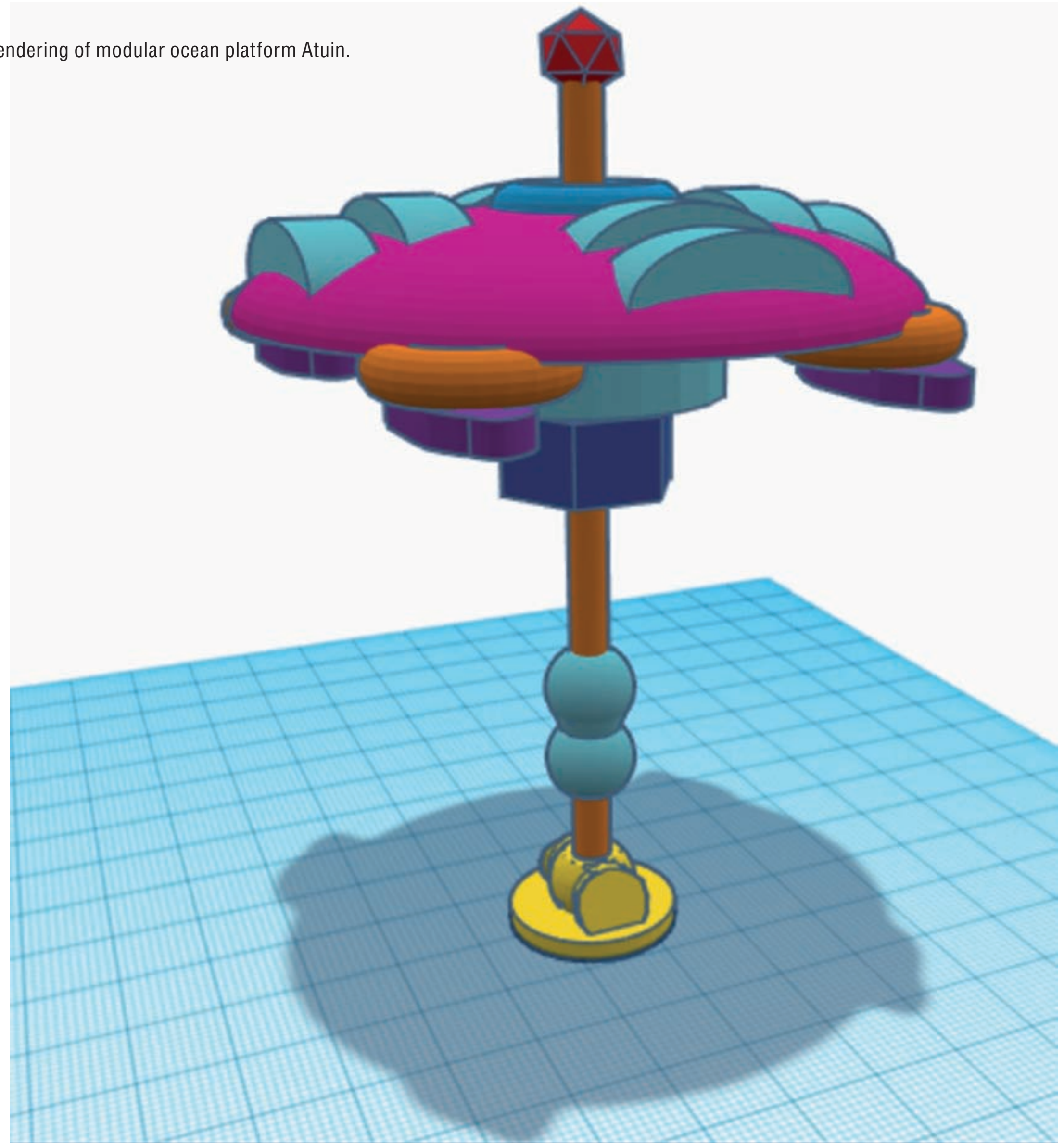

FIGURE 1. 3d rendering of modular ocean platform Atuin.

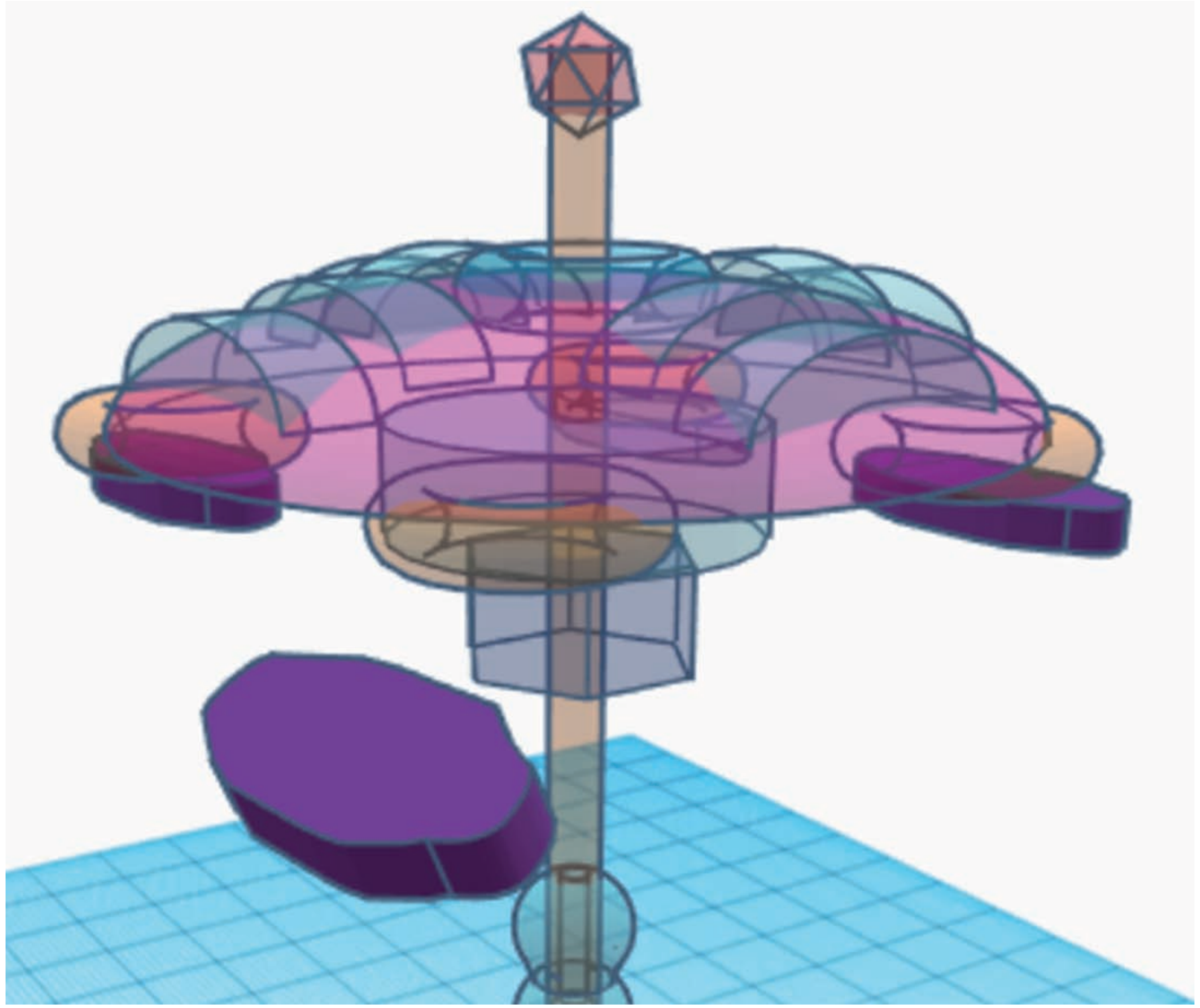

FIGURE 2. Rendering of AUV being deployed.

Vision and Potential Transformative Impact

By providing a tethered floating scientific platform that not only has passive, but also semi-autonomous data collection methods and protective measures such as a reactive 360 video camera, this treasure trove of science and conservation will be ideal for coastal and MPA observation and protection. Through developing deployments and long-term projects and applications with local stakeholders, those local entities will have ownership over the platforms, the projects, and the data collected, building an international community of data collectors.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

Working with groups like NOAA and universities, coastal deployment areas will be identified and piloted where more and more platforms will be deployed.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Data science, network science, and integrated data visualization as well as GIS technologies are all involved.

Opportunities for International Participation and Collaboration

Local stakeholders, international scientific and decision-making bodies and educational communities across the globe will be engaged.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

Through being a modular platform that packages its data and video stream in a report-based and curriculum-minded manner; new projects, applications, and even modules can be developed and deployed directly with ocean/biology/engineering educators and their students.

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Super Sites for Advancing Understanding of the Oceanic and Atmospheric Boundary Layers

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ABSTRACT

Air–sea interactions are critical to large-scale weather and climate predictions because of the ocean's ability to absorb excess atmospheric heat and carbon and regulate exchanges of momentum, water vapor, and other greenhouse gases. These exchanges are controlled by molecular, turbulent, and wave-driven processes in the atmospheric and oceanic boundary layers. Improved understanding and representation of these processes in models are key for increasing Earth system prediction skill, particularly for subseasonal to decadal time scales. Our understanding and ability to model these processes within this coupled system is presently inadequate due in large part to a lack of data: contemporaneous long-term observations from the top of the marine atmospheric boundary layer (MABL) to the base of the oceanic mixing layer.

We propose the concept of "Super Sites" to provide multi-year suites of measurements at specific locations to simultaneously characterize physical and biogeochemical processes within the coupled boundary layers at high spatial and temporal resolution. Measurements will be made from floating platforms, buoys, towers, and autonomous vehicles, utilizing both in-situ and remote sensors. The engineering challenges and level of coordination, integration, and interoperability required to develop these coupled ocean–atmosphere Super Sites place them in an "Ocean Shot" class.

Vision and Potential Transformative Impact

Super Sites will provide the long-term suites of state-of-the-art measurements that are critically needed to fully characterize coupled ocean–atmosphere boundary layer variability in different regimes of the climate system. This new measurement capability will provide the necessary data to allow us to improve and validate high-resolution atmosphere–ocean coupled models and satellite-based products; improve key process parameterizations for coarser-resolution models; and serve as a testbed for new and developing in-situ and remote sensors.

Testing and improving high-resolution models (which are essential for improving coarse-resolution climate simulations) requires statistically robust data samples over extended periods of time, which are not obtainable with typical short-term campaigns. Further, modeling needs require measurements that are often difficult to make due to specific platform, energy, and sensor needs. However, anchored and floating platforms are being developed that can support towers that span the boundary layers even over the open ocean. Moreover, these platforms will provide power to support newly-developed remote sensors and autonomous vehicles in the ocean and atmosphere to allow better 3D characterization of the coupled boundary layers.

Beyond sustained "core" observations, the Super Sites platforms will enable testing and validation of new technologies, serving as a catalyst for new scientific and engineering development.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

The U.S. oceanographic community has experience with some aspects of this type of sustained observational capability. Particularly, the United States has important contributions through experiences including the NSF-funded Ocean Observatories Initiative (OOI), which has made strides towards a combined, sustained mooring/glider program that samples the ocean and air–sea fluxes. The ONR-funded CBLAST program built a long-term Air–Sea Interaction Tower (ASIT) that continues to provide key coupled boundary layer observations after more than a decade. U.S. research vessels have provided platforms for many of the usable remote sensors. NASA/NOAA satellites measure key components of the air–sea interface, and a satellite designed specifically for the ABL is in incubation phase. The DOE has deep investment in wind energy technology,

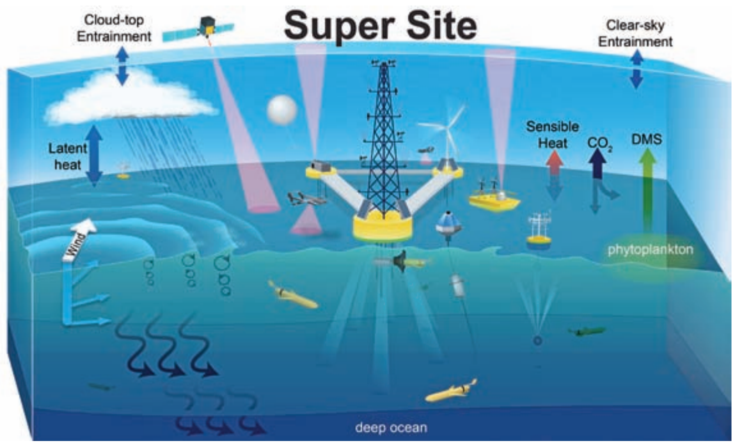

FIGURE 1. A schematic of possible types of deployments and instruments for a Super Site, including both passive and active atmospheric sensors, ocean gliders, atmospheric UAVs, multiple buoys, a central tower, wind- and solar-energy generating capabilities, and self-docking and charging AUV stations for multiple gliders.

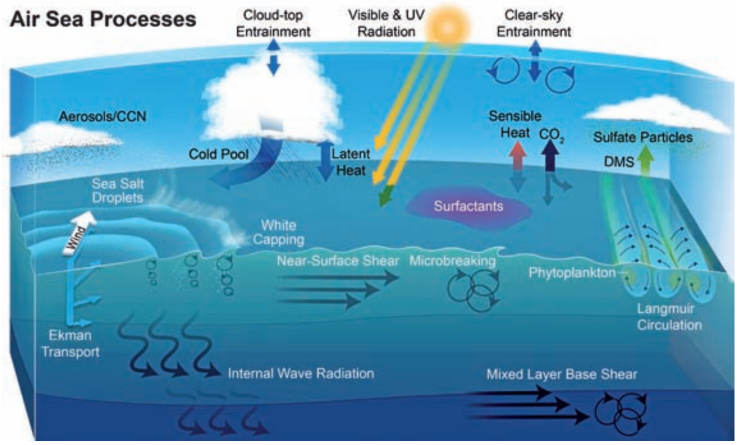

FIGURE 2. Schematic of key processes in the coupled ocean–atmosphere boundary layer system.

with a developing focus on offshore installations. The offshore wind industry is a clear example of a possible public–private partnership, with expertise in developing large platforms and delivering energy, as well as a vested interest in marine conditions and forecasts.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

The atmosphere–ocean coupled modeling community will be a key partner in the development and design of these Super Sites. In addition, atmospheric chemists, boundary layer meteorologists, cloud and radiation physicists, and remote sensing experts will be involved in their design and use. Creative engineering will be needed to envision and build all-new types of observing platforms with expanded power generation, data communications, and asset deployment capabilities. The telecommunications and informatics industries will be needed for expertise with the resulting big data. Industries associated with the development of autonomous platforms, drones, and sensors will also be key to Super Site success.

Opportunities for International Participation and Collaboration

Super Sites have been recommended by national and international groups, including the World Climate Research Program-Data Advisory Panel (WCRP-WDAC) surface flux team, OceanObs19 Community Strategy Papers, the Tropical Pacific Observing System (TPOS) Second Report, and the Observing Air–Sea Interactions Strategy (OASIS) SCOR Working Group. Super Site installations will be placed in carefully selected locations throughout the global oceans for several years and then relocated. Such a significant undertaking will require the expertise of the international community, working in partnership with local scientists, particularly for development and maintenance of the Super Sites, as well as any legacy observations.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers and Technologists

A key program aspect will be to engage and enhance the scientific and technical expertise of the scientific communities in the relevant local country(ies), as well as provide more general public educational opportunities. As a testbed for new platforms and sensors, some capacity will be reserved for both early career scientists and local scientists to propose and develop novel capabilities. The science defining exchanges between the upper ocean and the atmospheric boundary layer is a leading-order challenge. Super Sites will provide the scientific opportunities needed to train the next generation of ocean and atmospheric scientists to tackle these problems.

Funding: NOAA CVP TPOS, Understanding Processes Controlling Near-Surface Salinity in the Tropical Ocean Using Multiscale Coupled Modeling and Analysis, NA18OAR4310402 to CAC and JE. NSF Award PLR-1425989 and OPP-1936222, Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) to SG. NOAA, BOEM, ONR, NSF, NOPP, NASA Applied Sciences Office, Biodiversity & Ecological Forecasting Program; National Science Foundation (Co-PI J. Pearlman); OceanObs Research Coordination Network (OCE-1728913) to FM-K. NASA, SWOT program, Award # 80NSSC20K1136 to ABVB. NSF, Investigating the Air-Sea Energy Exchange in the presence of Surface Gravity Waves by Measurements of Turbulence Dissipation, Production and Transport, OCE 17-56839; NSF, A Multi-Spectral Thermal Infrared Imaging System for Air-Sea Interaction Research, OCE 20-23678; NSF, Investigating the Relationship Between Ocean Surface Gravity–Capillary Waves, Surface-Layer Hydrodynamics, and Air–Sea Momentum Flux, OCE 20-49579 to CJZ. Partially funded by NOAA/Climate Program Office and the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement NA15OAR4320063 to DZ.

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Advancing Ocean Science Through Open Science and Software on the Cloud

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ABSTRACT

This Ocean-Shot will seek to advance community awareness and practice around open science, based on the activities and outcomes generated by a growing cadre of U.S.-based and international developers working with open software libraries and in cloud computing environments. This practice will require additional software and tooling and required a shift in thinking toward a philosophy of trust and transparency. Key to this endeavor will be to take advantage of innovative development tools and practices that will better enable science by decreasing barriers to collaborations, reproducibility, and interdisciplinary research.

For data, this will mark a shift from a central repository model to central service model, enabling data-proximate computing. Most commonly today, data are downloaded from central locations for analysis on local environments. We hope to advance data-proximate computing that facilitates the accessing of data in central locations and running analysis there. This will mark a move from current reliance on locally deployed packages and servers to making products and services readily available on the cloud. The project will contribute to a step change of how datasets are accessed and used across the community. Throughout the decade it will build on the training and capacity development currently supported by NASA, and upon the professional development activities of other stakeholders.

Vision and Potential Transformative Impact

The primary goal is to improve the utility of ocean observing data and guide the community to the next generation of software development and data use on the cloud. Over the next decade, ocean observing must evolve to take advantage of the expanding availability and maturity of cloud computing, including the development of shared data processing workflows that utilize common, adaptable software to better handle data ingest and storage, and the associated frameworks to manage and execute downstream modeling. This initiative will begin by addressing challenges presented by working in the cloud: migration of legacy technologies and processes, cloud-to-cloud interoperability, as well as translation of legislative and bureaucratic requirements for "on-premises" cloud systems.

Mass storage of observational data, coupled with on-demand computing, the capability to run tools to manage workflows, and collaborative frameworks designed to facilitate the sharing of applications and knowledge tools will enable a more flexible and adaptable observation and prediction computing architecture. Leading to an environment where model outputs may be stored in the cloud and researchers feed data and code into their own simulations without leaving the cloud (Vance et al., 2019). More generally taking advantage of cloud platforms, services, and the interfaces provided will offer new ways for scientists to understand and predict the ocean.

Realizable, With Connections to Existing U.S. Scientific Infrastructure, Technology Development, and Public–Private Partnerships

In order to capitalize on existing open data policies and make widespread use of data and collaborative code available on the cloud, ocean data practitioners, data managers, software and application developers require a roadmap. Not only can the ocean science community take advantage of progress made by other scientific disciplines (e.g., atmosphere), but the shared and open platforms and tools will one day provide an opportunity for the community to develop its own practices and methodologies.

Based on an informal initial gap analysis conducted by a team of experts from key U.S. and international ocean science groups, there exists a need in the community to establish focused projects and trainings to further the development and adoption of methodologies and collaborations in cloud data and computing. This will involve a move from the current reliance on locally deployed services and applications, and servers to making products and services available on the cloud. This will result in a shift in reliance on individual bespoke or commercially developed software solutions to open solutions that—most importantly—can be deployed and further developed by anyone.

Over the course of the decade, large data providers such as NASA and NOAA are well poised to provide a leadership role in assisting groups in discovering these online environments as well developing and using the skills required to further facilitate the utility of data, application development, and knowledge sharing overall.

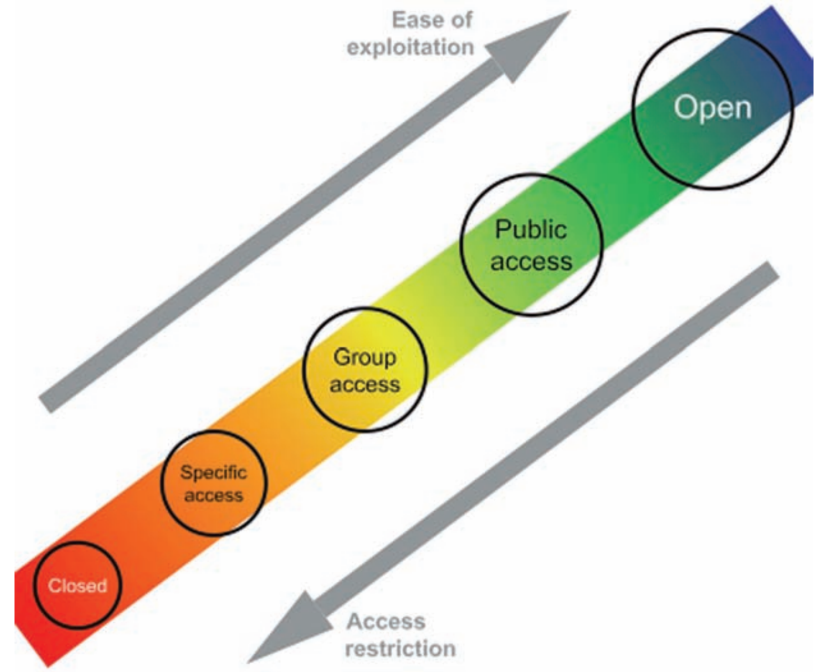

FIGURE 1. Roadmap to Open Science.

Scientific/Technological Sectors Engaged Outside of Traditional Ocean Sciences

Initially this practice will drive the ocean science community toward wider acceptance of ocean data and software development-sharing techniques through the promotion and identification of existing and new methods that provide credit for publishing of opensource resources. This will include promoting development of existing opensource oceanography and related libraries that enable oceanographers to advance their science. It will encompass all sectors of development, including federal employees working on opensource projects, funding work on libraries, or add-ons for grants.

Over the decade, this initiative will develop a suite of resources benefiting ocean observing, resulting in more effective use of data uptake within a plethora of applications and environments of greater benefit to the observing community.

For the near-term this will involve the development of cloud agnostic techniques that reduce barriers to cloud computing and to avoid vendor lock-in. As such the community is now challenged to create tools that support collaboration, enhanced, and streamlined data analysis, and speed software development. The community is also challenged to develop training and capacity development packages that support collaborative software development and code sharing through cloud computing.

Opportunities for International Participation and Collaboration

In addition to the transformative work that will be done in the United States, there are several international and overseas efforts that may be of benefit to this project, as well as benefit from this project (e.g., Copernicus, Ocean Predict). Working through existing and evolving programs led by international groups and organizations such as CEOS and GOOS (IODE, OCG), the project will identify specific areas for development and seek methods of collaboration through demonstrations or pilot projects. This may take the form of code and application development and may build upon the successful online, opensource hackathon held in October 2020.

Develops Global Capacity and Encourages the Development of the Next Generation of Ocean Scientists, Engineers, and Technologists

The project will result in a step change of how datasets are accessed and used across the globe. Throughout the decade it will build on the training and capacity development currently supported by NASA, and upon the professional development activities of other U.S. stakeholders. Through the collaborative activities managed by the project, additional training and development needs will be articulated and constant user feedback will be reflected in the evolution of sessions and approaches. Given the impact of COVID-19 in the early years of the decade, it is anticipated that much of this material will be generated for online delivery.

Reference

Vance, T.C., Wengren, M., Burger, E., Hernandez, D., Kearns, T., Medina-Lopez, E., … Wilcox, K. 2019. From the Oceans to the Cloud: Opportunities and Challenges for Data, Models, Computation and Workflows. Front. Mar. Sci., 6:211. https://doi.org/10.3389/fmars.2019.00211.

Relevant Ocean Decade Challenge(s):

- **Challenge 7:** Ensure a sustainable ocean observing system that delivers timely data and across all basins
- **Challenge 8:** Develop a comprehensive digital representation of the ocean
- **Challenge 9:** Ensure comprehensive capacity development and equitable access to data, information, knowledge, and technology

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