PAPER

The Deep Ocean Observing Strategy: Addressing Global Challenges in the Deep Sea Through Collaboration

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Introduction

The Science We Need for the Deep Ocean We Want

ABSTRACT

The Deep Ocean Observing Strategy (DOOS) is an international, community-driven initiative that facilitates collaboration across disciplines and fields, elevates a diverse cohort of early career researchers into future leaders, and connects scientific advancements to societal needs. DOOS represents a global network of deep-ocean observing, mapping, and modeling experts, focusing community efforts in the support of strong science, policy, and planning for sustainable oceans. Its initiatives work to propose deep-sea Essential Ocean Variables; assess technology development; develop shared best practices, standards, and cross-calibration procedures; and transfer knowledge to policy makers and deep-ocean stakeholders. Several of these efforts align with the vision of the UN Ocean Decade to generate the science we need to create the *deep* ocean we want. DOOS works toward (1) a *healthy and resilient deep* ocean by informing science-based conservation actions, including optimizing data delivery, creating habitat and ecological maps of critical areas, and developing regional demonstration projects; (2) a *predicted deep* ocean by strengthening collaborations within the modeling community, determining needs for interdisciplinary modeling and observing system assessment in the deep ocean; (3) an *accessible deep* ocean by enhancing open access to innovative low-cost sensors and open-source plans, making deep-ocean data Findable, Accessible, Interoperable, and Reusable, and focusing on capacity development in developing countries; and finally (4) an *inspiring and engaging deep* ocean by translating science to stakeholders/end users and informing policy and management decisions, including in international waters.

Keywords: deep ocean, ocean observing, multi-disciplinary, science policy and planning, FAIR data principles

The deep ocean is among the last frontiers for exploration on our planet. To put this in perspective, we have better maps of several planets in our solar system than we do of the seafloor (Mayer et al., 2018), and most deep sea biodiversity has yet to be described (Howell et al., 2020, 2021). Though vastly underexplored, the importance of the deep sea is undeniable. When it comes to climate regulation, deep-ocean circulation is crucial: deep water masses below 2,000 m occupy > 50% of the ocean volume, constitute the largest carbon reservoir, store massive amounts of excess heat, and contribute to sea level rise via thermal expansion (Cross-Chapter Box 9.1.1; Fox-Kemper et al., 2021). Abyssal mixing determines ocean stratification and, through it, the global overturning circulation (Whalen et al., 2020). At the same time, the deep ocean houses a wealth of hydrocarbon, mineral, and genetic resources and is thus not only threatened by climate change but also subject to rising interest in resource exploitation (Mengerink et al., 2014; Ramirez-Llodra et al., 2011). The sustained monitoring of the deep ocean and its services into the future is essential for advancing our scientific knowledge of its current state and determining how it is changing. Given the significant technical and logistical challenges faced for deep-ocean observations, coordination is needed to observe and preserve the deep ocean we want (Levin, Bett, et al., 2019). The future of deep-ocean observations relies on integration across traditional disciplines and sectors, elevating new voices into the discussion, and the open sharing of knowledge, resources, data, and technical innovation.

The Deep Ocean Observing Strategy (DOOS) was formed in 2014 as a Global Ocean Observing System[1] (GOOS) project. DOOS is working as an endorsed program of the United Nations Decade of Ocean Science for Sustainable Development (hereafter "Ocean Decade"), to coordinate and promote a globally integrated network of networks that can observe the deep ocean[2] effectively in support of strong science, policy, and planning for sustainable oceans. DOOS represents a coalition of international deep-ocean stakeholders from science, management, government, and industry for waters within and beyond national jurisdiction (Figure 1). It includes researchers from across observing, exploration, modeling, data, and informatics communities. DOOS puts a particular emphasis on the promotion of early-career researchers (ECRs) into leadership positions and bringing to the table those traditionally left out of these discussions, such as women and under-represented communities as well as individuals from middle- and lower-income countries.

[1]https://www.goosocean.org/

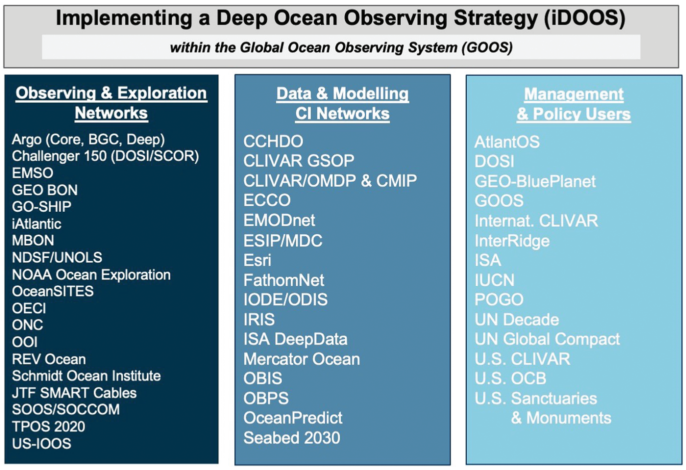
[2]DOOS defines "deep ocean" as the area below the main thermocline (>2,000 m), with additional attention to shallower processes and mechanisms that are poorly sampled below the photic zone (>200 m) that influence the deeper depths.

Building a Network of Networks

Creating a deep ocean network of networks involves (1) acting as an agent to coordinate existing deep observing activities across disciplines to form an effective, sustained, deep-ocean observing effort; (2) acting as

FIGURE 1

DOOS Network of Networks. DOOS represents a global network of deep-ocean observing, mapping, and modeling experts, focusing community efforts in the support of strong science, policy, and planning for sustainable oceans. Though not an exhaustive list, these are many of the community groups part of the DOOS Network of Networks.

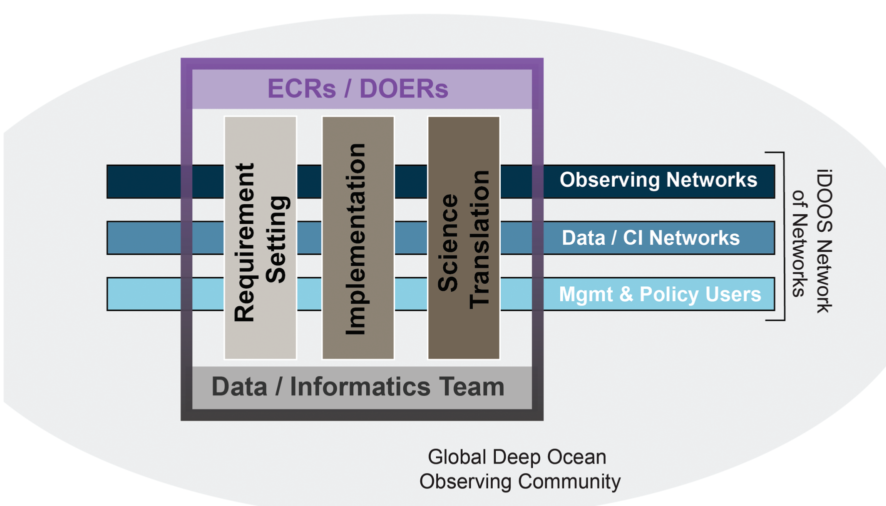


an integrator to create linkages among research, intergovernmental, industry, regulatory, and funding agencies to achieve deep-ocean societal objectives through science; and (3) fostering observing activities and demonstrating integrated approaches at community identified multi-use, multi-disciplinary sites, representing different key climate, biogeochemical (BGC), and ecological regimes and questions. These actions allow DOOS to coordinate research priorities and resources across the deep sea community to address knowledge gaps and needs in deep-ocean observing, positioning the community to continue future work for decades to come.

In 2021, DOOS received funding from the U.S. National Science Foundation AccelNet program to further ongoing efforts to create a network of networks across disciplines, sectors, and communities involved in the deep sea to accelerate deep-ocean science. This project, iDOOS[3] (*implementing* DOOS), targets three overarching themes: (1) requirement setting for a fit-for-purpose deep-ocean observing system that meets the needs of science and society, (2) implementation of deep-ocean observations, and (3) transfer of scientific knowledge to stakeholders including business, policy makers, and civil society to promote science-based decision making (Figure 2). Superimposed on each of these thematic efforts are cross-cutting activities to develop the next generation of deep ocean observing leaders and advance frameworks that promote the Findability, Accessibility, Interoperability, and Reusability (FAIR; Wilkinson et al., 2016) of deep-sea data.

FIGURE 2

Schematic of iDOOS themes and networks. The DOOS Network of Networks outlined in Figure 1 becomes the horizontal blue boxes on this figure. Cutting across these networks are the three main themes of DOOS efforts—requirement setting, implementation, and science translation. Superimposed on these themes are cross-cutting activities of data and ECRs.



Coordinating a Deep-Ocean Observing Strategy

Coordination between numerous research groups, observation systems, and data standards often make research and communication among researchers, users, and policymakers challenging. Consequently, constant effort is required to improve communication among all stakeholders, standardize datasets, methodology, and

[3]iDOOS is merely the name assigned to this funding, these efforts continue DOOS' existing efforts and in this way DOOS and iDOOS can be seen as one in the same thing. As such we will simply use "DOOS" in the remainder of the article.

technology, and coordinate cross-disciplinary procedures focused on datasets from models and observational systems. DOOS builds upon ongoing efforts of best practices, standards, and cross-calibration procedures through a critical partnership with the Ocean Best Practices System (OBPS) for the Decade program (Pearlman et al., 2019, 2021) and the creation of a deep-ocean best practices task team. Rather than developing new specifications and standards, DOOS uses existing OBPS standardized templates to refine and guide a set of standards (Hörtsmann et al., 2020), identifying best-proven and feasible efforts across different networks that may be leveraged to improve the quality and accessibility of deep ocean data. These efforts encompass defining a deep-ocean set of Essential Ocean Variables (EOVs) as well standardization of technology.

EOVs are a core set of variables selected and approved by GOOS expert panels[4] adopting the Framework for Ocean Observing (Lindstrom et al., 2012) to focus and harmonize global observing efforts. These variables must be relevant to address societal and scientific needs, technically feasible to produce on a global scale using demonstrated and scientifically accepted methods, and affordable to generate and archive within coordinated observing systems. EOVs are vital in deep ocean research due to the need to avoid duplication of efforts and adopt common standards to maximize utility of data when studying such an enormous, remote, and difficult system, especially when the costs involved in collecting such data can be prohibitive.

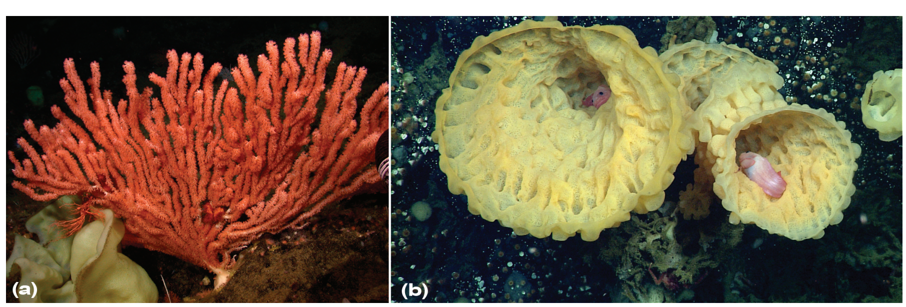
Two of the main objectives of DOOS in this area are to (1) to examine existing EOVs in terms of special requirements for deep-sea research, in order to add a deep-ocean perspective that is missing from or is underrepresented in existing GOOS EOVs, and (2) work with the DOOS networks in line with the Framework for Ocean Observing to draft EOV specifications supporting documentation for a prospective set of physical, BGC, and biological/ecological EOVs considered crucial for deep-ocean observing. Prospective deep-sea EOVs proposed by DOOS are drafted using GOOS specification sheets and following the GOOS framework. They are then reviewed by GOOS expert panels to determine whether they have reached a level of maturity and feasibility impact that fulfills the criteria for acceptance as a new EOV (or addition to existing variables).

Prospective variables being examined by DOOS are separated into three disciplines. The physics variables are ocean bottom pressure, turbulence, and seafloor flux; the BGC variables are seafloor respiration, seafloor labile organic matter, and methane; and the biology and ecosystem (BioEco) variables are invertebrate abundance and distribution (already an emerging EOV with GOOS), deep/cold water coral cover and composition, and sponge cover and composition (Figure 3). Following submission of the proposed deep-sea EOVs, DOOS will also provide road maps to help guide implementation, which are focused on global scale observing programs (e.g., Argo), cabled or moored ocean observatories (e.g., the Ocean Observatories Initiative and Ocean Networks Canada, OceanSITES, JTF SMART Cables; Howe et al., 2022), and distributed mobile platforms (e.g., remotely operated vehicles and autonomous underwater vehicles), including those where sensors are attached to marine mammals (e.g., MEOP Consortium–Marine Mammals Exploring the Oceans Pole to Pole).

Developing standards for deep-sea measurements must be coupled with technology readiness and accessibility in order to implement distributed global-scale deep ocean observations (e.g., a range of operators, scientists, and citizens). An array of fixed and mobile platforms can be used to carry sensors for observing and

FIGURE 3

(a) This pink bamboo coral (*Keratoisis sp.*) is one of the most common bamboo corals MBARI encounters during our exploration of the deep sea. Image: © 2004 MBARI, (b) Snailfish (*Careproctus kamikawai*) have found the perfect hiding spot in a pair of elongate goiter sponges, *Heterochone calyx*. This photo was taken at Sur Ridge, approximately 35 miles off the Big Sur coast at 1,127 m deep. Image: © 2013 MBARI.



[4]https://www.goosocean.org/index.php?option=com_content&view=article&id=286&Itemid=422

measuring EOVs as well as other deep-ocean observations. The maturation of both sensors and platforms has progressed considerably in the last decade with many vendors now providing solutions suitable for deep-sea deployment as part of their regular product line. Together, these provide a wide range of enhancements for observing the deep ocean. Opportunities for improved observation are offered by recent advances in low-energy and low-cost miniaturized sensors, batteries, and robotics that facilitate developments to expand the network of autonomous monitored stations. Examples include observations of global water masses with the Argo, BGC Argo, and Deep Argo programs and multidisciplinary surveying of the seafloor and the lowermost water column through emerging networks of seafloor observing platforms. For example, benthic crawlers—i.e., mobile benthic platforms that host a variety of payload including instruments for respiration studies and mapping of phytodetritus that is supplied to the seafloor from the water column—are deployed for long-term, unattended observations (Figure 4). Further opportunities arise from improvements in acoustic and optical communications from the ocean interior to the sea surface, and the potential of communication and power by new and reused telecommunications cable networks (Howe et al., 2022).

Addressing Global Challenges in the Deep Sea

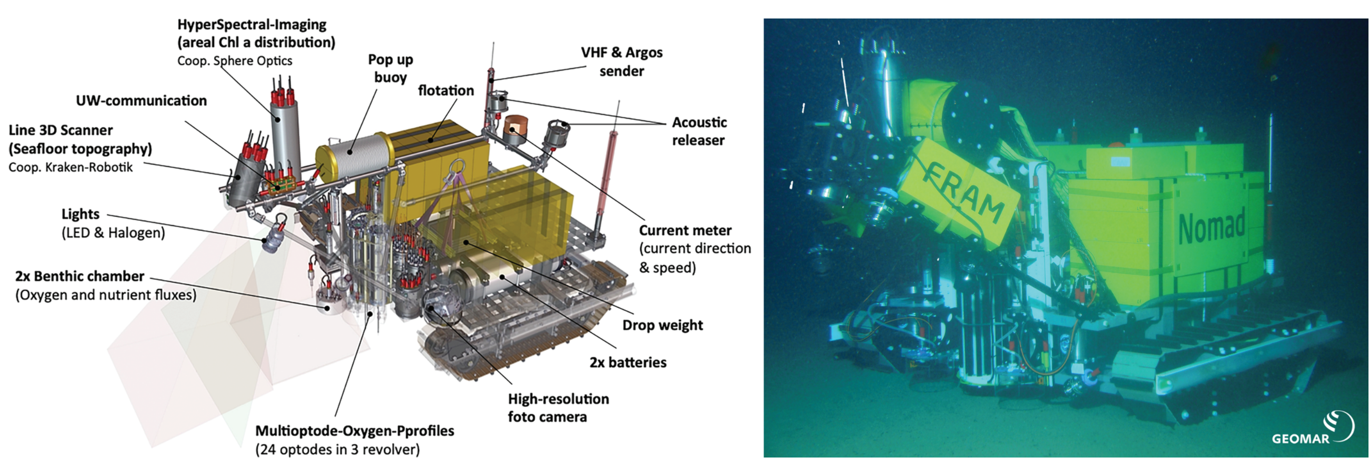
DOOS operates through a series of working groups that each address a global deep-sea challenge. These working groups were designed with community input to determine priority actions that leverage existing research efforts and resources, in order to address defined challenges and gaps together. Ultimately, they seek to accelerate the development and use of deep-sea observational data by breaking down barriers and building new partnerships across countries, networks, disciplines, and communities. In the following sections, DOOS working group efforts are described, as they align with the vision of the Ocean Decade.

A Healthy and Resilient Deep Ocean

Exploration, observing, and monitoring are necessary for effective environmental management and conservation planning (National Research Council, 1990). There is currently much debate about whether the state of knowledge about deep-sea environments and ecosystem processes is sufficient to guarantee equitable, safe, and sustainable exploitation of the fisheries, minerals, and energy resources in the deep ocean (Amon, Gollner, et al., 2022; Ramirez-Llodra et al., 2011). Stakeholders, including scientists, increasingly recognize the need to incorporate knowledge of climate-driven change into deep-sea conservation planning (Le Bris & Levin, 2020; Morato et al., 2020), environmental management of fisheries (Levin, Baker, et al., 2019),

FIGURE 4

At several institutions worldwide, autonomous benthic platforms are developed and used for time series measurements of benthic biogeochemistry, including suggested "DOOS EOVs" seafloor respiration (with benthic chambers and / or microsensor-profilers) and seafloor labile organic matter (with optical methods). The figure shows the benthic crawler NOMAD developed for year-round measurements at high latitudes (Lemburg et al., 2018) as an example. The right panel shows NOMAD during a deployment at the FRAM deep-sea observatory in the Arctic in 2019 (underwater photograph courtesy of GEOMAR ROV Phoca team).



and minerals extraction (Dunn et al., 2018; Levin et al., 2020).

The UN Agenda 2030 that hosts the Sustainable Development Goals, the UN Decade of Ocean Science, and the joint IPCC (Intergovernmental Panel on Climate Change)–IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) report (Pörtner et al., 2021), among others, all identify the critical need to address the interconnected issues of biodiversity, climate, and ocean health. Simultaneously, it is necessary to understand how resource extraction and area-based protections affect the carbon cycle and feedback to climate. It is critical as we navigate conservation and sustainable use of marine biodiversity, particularly in areas beyond national jurisdiction, to incorporate scientific knowledge in that decision-making process (Harden-Davies, 2017). For example, changes in habitat suitability that influence species connectivity can be particularly important when considering the design of Marine Protected Areas (MPAs) as these changes can impact an MPA's ability to internally maintain populations (Fox et al., 2016; Rengstorf et al., 2013; Stuart et al., 2021). Increasing the understanding of connectivity of species into and out of MPAs can thus inform the design of future MPA networks in national waters and areas beyond national jurisdiction. Currently, DOOS is working to facilitate several Demonstration Projects as well as a specific ecosystem-level effort in a U.S. National Marine Sanctuary to address challenges of a healthy and resilient ocean. Each of these have the aim that the lessons learned during these projects can be scaled up and expanded to the global level with additional efforts made to translate this information to policymakers and stakeholders.

Ecosystem Indicators and Mapping

Up-to-date information on the status and trends of ocean change is important to make informed decisions on conservation and sustainability. However, challenges remain in delivering timely observations for the deep ocean and many habitat and ecological mapping tools must be revised to understand change in the ocean and predict benthic species distribution and assess the vulnerability of communities to these changes. To tackle these challenges, DOOS is conducting two regional pilot efforts in the Monterey Bay National Marine Sanctuary (MBNMS). The MBNMS is located off the West Coast of the United States and contains several deep-water areas of particular geological and biological significance, including Sur Ridge and Davidson Seamount, as well as nearby areas with offshore energy exploration and development. This pilot effort is focused on data stream planning to optimize end-user needs, including the application of habitat and ecological mapping.

A key element of making deep-sea data open and accessible requires scientists to actively identify users of deep-ocean data, learn to assess interests, requirements, and priorities, and co-design pathways for shared data access. Scientists and managers affiliated with the sanctuary have developed a list of indicators specific to the deep-ocean environment that they require to assess the status and trend of ocean change in MBNMS (ONMS, 2018; Ruhl et al., 2021). However, from the sanctuary's perspective, data are lacking for many of these indicators. DOOS is working to integrate FAIR data practices (Wilkinson et al., 2016) with human-centered design principles to improve access to deep ocean data and develop tailored data products to meet MBNMS needs. To improve data delivery to researchers, managers, and policy makers, DOOS is working to (1) crosswalk regional, national, and global observing priorities and indicators; (2) identify existing data that could inform these indicators; and (3) design and facilitate FAIR data pipelines; i.e., established series of technologies and processing steps that are used to reliably transfer data from the provider to the end user and transform, store, and display it according to the end user's needs. Each of these steps require close collaboration with both data users and providers. From this work, DOOS seeks to connect data sets with end users in a collaborative way that ensures timely and useful data delivery.

Similarly, habitat and ecological mapping are critical tools for protecting and managing ocean ecosystems. Both benthic and pelagic systems are strongly influenced by the bathymetry, morphology, substratum type, granulometry of the seafloor, and benthopelagic circulation (e.g., McQuaid et al., 2020; Morris et al., 2016). Thus, information on physical, BGC, biological, and ecosystem conditions in pelagic and benthic habitats help researchers map, classify, and understand change in the ocean (e.g., Diaz et al., 2004; Plonus et al., 2021) as well as predict benthic species distribution and assess the vulnerability of communities to these changes. Developing and revising habitat and ecological mapping tools to define habitat classes, ecological biotopes, and thereby statistical strata (bins) in space and time can clarify how existing and prospective observing activities and assets can inform on variation in these strata. This can be used to identify where new efforts are needed to fill data gaps, and it can help build analytical skill toward specific applications, such as estimating size-specific biomass at the seabed. Constructing these strata can also inform how remote sensing, in-situ observations, and modeling can be used together in observing system design and data and information product development. Initial DOOS efforts focus on assessing the spatial and temporal scales of existing habitat maps. Ultimately, we not only hope to use these empirical data to improve habitat maps and classifications for the region but also to create a set of processes and best practices that can be utilized in other protected areas around the globe.

The lessons learned from both pilot activities in the MBNMS will be applied to other DOOS efforts and ultimately generalized as a set of guidelines that can inform co-design of data delivery systems for deep-water managed areas around the world.

Demonstration Projects

The deep ocean hosts a diverse set of habitats, from trenches to seamounts and abyssal plains to slopes. DOOS focuses on several of these habitats through its Demonstration Projects. DOOS Demonstration Projects seek to provide rallying points for the deep-ocean community to integrate and coordinate deep-ocean observing efforts to address large challenges in the deep sea. To this end, these projects bring together groups from across exploration, observation, monitoring, and modeling communities to leverage and integrate infrastructure and resources. The goal is to assess what can be accomplished if collective efforts of the deep-ocean community, already working in an area, could be focused toward the same aim and integrated with new activities being attracted to join the community effort. Each project highlights measurements of EOVs across disciplines, enables testing of new technologies, evaluates data accessibility, ties together disparate existing programs and communities, and demonstrates the benefits of deep-ocean knowledge for policy, management, conservation, and the private sector. These localized projects are designed to expand and inform approaches at a global scale. To date, two demonstration projects are actively pursued by DOOS, each with a working group and community actions currently underway. The first of these projects focuses on assessing biodiversity in deep-sea benthic communities in the Azores Archipelago in the context of a changing climate and other anthropogenic stressors, and the second focuses on the impacts of meridional overturning circulation on the biogeochemistry and biology of the subpolar North Atlantic.

Due to its unique geographic and oceanographic setting, including the proximity to diverse open-ocean and deep-sea habitats, the Azores Archipelago serves as a natural laboratory to address gaps in knowledge on the relationships between deep-sea environmental properties, biodiversity, and ecosystem functions (Morato et al., 2016; Peran et al., 2016). Although MPAs were established in the Azores in the 1980s, the increased economic opportunities in the deep sea (e.g., fishing, bio-prospecting and mining) have led to additional observation needs to inform management and conservation efforts, particularly in the context of changing ocean conditions (e.g., warming, acidification, deoxygenation). In order to address these challenges, DOOS, in cooperation with the All-Atlantic Ocean Observing System (AtlantOS; deYoung et al., 2019) as well as local and international scientists and stakeholders, has developed a Demonstration Project to implement holistic ecosystem observations in the wider Azores area. The project theme, which was defined through a community scoping workshop in June 2021, explores the spatial distribution of the benthic communities, the factors driving it, and the evolution of the system in response to global change and current and future uses.

The subpolar North Atlantic plays a critical role in regulating the climate system. Ventilation within this region connects the atmosphere to the ocean interior, shaping the sequestration and redistribution of heat and carbon dioxide (Sabine et al. 2004, Zanna et al., 2019) on sub-annual to centennial timescales (Gebbie & Huybers, 2011). Although extensively observed when compared to other ocean basins, the region is characterized by pronounced multidecadal variability (Robson et al., 2018), which complicates local detection and attribution of climate change. DOOS has developed a Demonstration Project in this region to examine critical observation gaps impeding these assessments and conduct coordinated observing system experiments to understand the constraint provided by existing observational networks. Two noteworthy examples here are (1) the Overturning in the Subpolar North Atlantic Program (Lozier et al., 2017, 2019) and (2) the Bottom Boundary Layer Turbulence and Abyssal Recipes Project,[5] which address fundamental questions surrounding pathways of overturning circulation and mechanisms of large-scale mixing and upwelling, respectively. Another core component of this Demonstration Project is to coordinate

[5]https://oceanmixing.github.io/projects/blt/

numerical experiments to test future instrument deployments in support of effective and sustainable long-term monitoring of circulation, heat, and BGC exchanges. A key goal here is to investigate best sampling strategies to monitor temperature, salinity, and oxygen variability through the full depth of the water column, in close collaboration with the Deep Argo Mission Team.

Two additional demonstration projects have been proposed for future consideration: the Clarion-Clipperton Zone (CCZ), an abyssal plain in the eastern tropical North Pacific, and the Cascadia Margin and Juan de Fuca Plate in the northeast Pacific. The former is located on a fracture zone with polymetallic nodule mining potential in the central eastern Pacific (Lodge et al., 2014) and is of great interest to the International Seabed Authority (ISA). Data from such a Demonstration Project could feed into the current Environmental Management Plan for the CCZ (ISA, 2012), informing stakeholders of the environmental setting and contributing to assessing the consequences of nodule mining. Although recurrent baseline observations are carried out by individual contractors, including deployments of oceanographic moorings (Aleynik et al., 2017), the CCZ lacks sustained long-term observatory infrastructures. Conversely, the NE Pacific provides an ideal site for a Demonstration Project because of its two sustained, long-term cabled observatories, the U.S. NSF Ocean Observatories Initiative Regional Cabled Array and the Ocean Networks Canada Neptune observatory. These provide unprecedented opportunities for an in-depth regional study spanning an entire tectonic plate. Habitat areas include widely contrasting pelagic and benthic physical and biological regimes, methane seep sites, the subduction zone, active hydrothermal vents, and Axial Seamount, an active volcano on the Juan de Fuca Ridge.

A Predicted Deep Ocean

The ability of the ocean to mitigate climate changes is directly dependent on the strength and variability of its overturning circulation, which contributes to the global redistribution of heat, carbon, and nutrients. With more than 90% of the anthropogenic heat imbalance absorbed by the ocean (Levitus et al., 2012), accurately monitoring ocean heat content across the full ocean depth provides a fundamental constraint on quantifying the warming of the planet and its effect on sea-level rise (Johnson et al., 2016; Purkey & Johnson, 2010; Zanna et al., 2019). The deep ocean is earth's largest carbon reservoir and the sinking of dense waters from the ocean surface to the deep is a pathway for anthropogenic carbon to be sequestered from the atmosphere on centennial timescales (Gruber et al., 2019), such as through the biological carbon pump. Climate change also has direct and indirect impacts on ocean biodiversity: deep-ocean biodiversity loss and climate-induced regime shifts are already occurring in some areas and are anticipated elsewhere (Levin & Le Bris, 2015), while climate change-induced acidification and deoxygenation can lead to global alteration of ecosystem functioning (e.g., Booth et al., 2018; Nagelkerken & Connell, 2015; Schofield et al., 2010).

Despite its importance in climate regulation, the deep ocean is poorly sampled due to several observational challenges, and available data are often limited to spatially distant hydrographic sections sampled once every decade. In fact, the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate identifies response of deep seafloor ecosystems to climate change as a key knowledge gap (Bindoff et al., 2019). Because of this paucity of data, which leads to large uncertainties in addressing changes at depth, and its remote nature, the deep ocean is often not well considered in global climate change discussions (Levin, 2021).

Deep observing will also play a key role in documenting the effectiveness and potential deep-sea impacts of ocean-based climate mitigation approaches that are currently under consideration such as iron fertilization, seaweed culture and sinking, alkalinity addition, artificial upwelling, and subsurface CO_2 injection (GESAMP, 2019). Our ability to project future change and develop adaptation and mitigation strategies to better enable society to cope with climate change would be greatly enhanced by new, well-coordinated physical, BGC, and biological observations in deep waters.

State-of-the-art global climate models provide invaluable scenarios of future deep ocean change. Despite significant advances in recent decades, numerous issues hinder the use of these models for essential ecosystem science and living marine resource management applications (Drenkard et al., 2021). These issues include large regional biases (Fox-Kemper et al., 2019; Stock et al., 2011), missed or over-simplified system couplings, and inadequacies in shared model output. Additionally, improving our understanding of the deep ocean demands sustained high-quality observations of multiple variables, across disciplines, over a large range of spatial scales, necessitating careful allocation of resources to maintain existing networks and support new deployments.

DOOS efforts to create a predicted deep ocean include (1) identifying major observational gaps (in space and time) that prevent us from investigating the mean-state and the decadal to interannual variability of deep-ocean physics, chemistry and biogeochemistry; (2) facilitating networking across observational and modeling platforms to overcome such observational gaps; and (3) identifying key efforts needed to mitigate current observational gaps and find solutions for different networks to contribute to an integrated observing system.

The tight coupling between BGC properties, ocean circulation, and life in the deep sea and at the seafloor calls for coordinated numerical simulation experiments and extensive exchange of data and knowledge across ocean modeling disciplines. Advanced modeling network structures exist in the physical and BGC communities to support these exchanges. These include the International Climate and Ocean: Variability, Predictability and Change (CLIVAR) Ocean Model Development Panel (Fox-Kemper et al., 2019; Tsujino et al., 2020), and United Nations Educational, Scientific and Cultural Organization/Intergovernmental Oceanographic Commission (UNESCO/IOC) OceanPredict program (Davidson et al., 2019), which contribute to the Climate Model Intercomparison Project (Eyring et al., 2016), the IPCC, as well as national programs (e.g., Benway & Doney, 2014; Dunne et al., 2019; U.S. CLIVAR, 2013; U.S. Ocean Carbon & Biogeochemistry) and ocean forecasting and reanalysis centers (Subramanian et al., 2019). By comparison, ocean ecosystems, habitat, and biodiversity modeling efforts lack such coordination.

To address this, DOOS seeks to elevate ecological modeling by identifying and tackling critical factors inhibiting skillful simulation of the interconnected ocean system. Efforts include identifying key information required for the development and evaluation of individual model components and their dependencies, such as data gaps in the observational record and missing exchanges of data/knowledge/needs between communities. Identified data gaps will be fed into DOOS proposals for new deep EOVs. Recognition of missing exchanges will be used to co-design best practices for improved coordination between modeling communities to better understand and manage ocean ecosystems and living marine resources under climate change.

Additionally, models offer a formal framework for objectively assessing both observational priorities (Haine, 2020) and observation impacts (e.g., Gasparin et al., 2020; Nguyen et al., 2020). Emerging methods are now elucidating dynamical mechanisms underpinning impactful data acquisitions (Loose et al., 2020, Loose & Heimbach, 2021) to help guide these decisions with increased confidence. One major goal of these efforts is to determine how model-based predictions inform observational priorities, using existing output from state-of-the-art ensembles to build chronologies of future change in key deep ocean metrics (Jahn & Laiho, 2020). A second goal is to coordinate data-assimilating experiments (e.g., Fujii et al., 2019) to extract information from diverse, heterogenous deep ocean data sets and test the efficacy of future DOOS extensions.

An Accessible Deep Ocean

A continuing challenge for deep-sea science is to be inclusive, equitable, relevant, and accessible to all. Deep-sea science has traditionally rested in the domain of wealthy, mostly Northern Hemisphere countries (Amon, Rotjan, et al., 2022). DOOS is addressing the challenges of creating an accessible deep ocean by working toward making deep ocean data more FAIR, facilitating open access to technology and innovation, promoting capacity development efforts, and training the future leaders of the deep ocean through the Deep Ocean Early Career Researchers (DOERs) program (see Through Decade and Beyond to the Next Generation section).

Making Deep-Ocean Data More Findable, Accessible, Interoperable, and Reusable

The fundamental output of ocean observing is data. These data are used in many ways: to develop or test hypotheses, to initiate or evaluate models, to aggregate into larger syntheses, or to inform policy, management, and industry. A global understanding of the deep ocean, whether from the perspective of deep-water formation patterns, heat budgets, acidification, or biodiversity patterns, requires the integration of data from many observatories and research programs. Furthermore, observations in the deep ocean are so sparse and expensive that available data must be shared and reused for the field to progress. For these reasons, it is critical that deep-ocean data be preserved, trusted, and widely accessible to a broad spectrum of users.

The SeaFAIRer team is a cross-cutting group within DOOS: it works to ensure that FAIR principles and data-related best practices are an integral part of all DOOS initiatives and activities. Additionally, it serves to identify and address opportunities for improved progress toward FAIR data within and across the global and deep-ocean observing community cyberinfrastructures. Lastly, efforts of this group focus on training future leaders in the deep-ocean community to promote data and informatics literacy in the DOOS early-career professional development program via hands-on exercises and culminating in an in-person hackathon.

One specific data challenge that is being addressed is the coordination and sharing of data for higher trophic-level pelagic species. While it is challenging to manage and integrate ocean data in general, data about the diversity, abundance, and movement of higher trophic-level pelagics such as fishes and marine mammals are particularly formidable. Still images, video, eDNA, and passive and active acoustics produce large files, are difficult to integrate because of their heterogeneity, and/or require sophisticated and compute-intensive approaches to analyze (e.g., Frasier, 2021; Haris et al., 2021; Parsons et al., 2022; Robinson et al., 2021; Visser et al., 2021). Metadata describing data products generated from these types of datasets have often not been fully standardized and hence comparability becomes difficult (e.g., Roch et al., 2016). DOOS will bring together observational groups collecting these data, repositories storing and providing access, and scientists interested in using the data to collectively define a pathway to improved access and interoperability, and ultimately support new and better science.

Open Access to Technology and Innovation

The DOOS Technology Working Group focuses on deep-ocean observing technology awareness, development, and readiness levels. This working group has three main goals: (1) design sensor packages that can sample a core set of cross-disciplinary, deep-ocean-focused EOVs across multiple key depth intervals (e.g., 200 m, 4,000 m, 6,000 m), and align these needs with other DOOS themes and working groups; (2) examine, survey, and prioritize existing deep-ocean observing technologies that could support such a sensor suite in terms of readiness levels and the accessibility of that package across ocean users (e.g., cost and operability); and (3) identify gaps in existing technologies vs. sensing needs and forge pathways toward developing solutions. The result will be open source plans and diagrams of these packages as well as publications discussing individual technologies as appropriate. Examples of recent advances in deep-sea technologies that will serve these efforts include low-cost computing and sensing packages (e.g., Dominguez-Carrió et al., 2021; Phillips et al., 2019; Sugar et al., 2020), lander-based sensing platforms (e.g., Giddens et al., 2021; Jamieson et al., 2009; Wheeler et al., 2021;), 3D-printed pressure housings and in-field technology development pathways (e.g., Phillips et al., 2020), open-source image processing databases (Katija et al., 2021), and training workflows to increase global capacity in deep-sea accession (Amon, Gollner, et al., 2022).

Capacity Development for Developing and Middle-Income Countries

Through collaboration with the Ocean Discovery League (ODL), the DOERs Program (see Through Decade and Beyond to the Next Generation section), as well as various UN Ocean Decade vehicles (Stakeholder Forum, Early Career Ocean Professionals [ECOP], Communities of Practice), DOOS will raise awareness about the importance of the deep ocean around the world, transfer technology to and engage, mentor, and promote scientists from countries that normally have limited deep-sea access.

DOOS' partnership with ODL is critical to explore deep-ocean science and capacity needs globally. The Global Deep-Sea Capacity Assessment (an Ocean Decade Action) conducted in 2021 by ODL aimed to establish a baseline of global deep sea technical and human capacity so that we can (1) effectively plan and execute programs to increase capacity in historically excluded nations and communities, and (2) quantitatively measure the impact of the Ocean Decade on deep-sea science and exploration capacity. The assessment is the broadest survey on current capabilities to explore and study the deep sea, including data survey and/or research data on 187 countries and territories, of which 133 are developing economies and Small Island Developing States. Assessment data include a combination of 360 survey responses from 124 countries and territories, as well as detailed research on 182 coastal countries and territories with deep ocean in their exclusive economic zone conducted by a global team of research assistants. The online survey included 42 questions that were both quantitative and qualitative on human expertise and technical resources for deep-sea exploration such as vessels, deep submergence vehicles, sensors, and data analysis capacities. The survey was offered in four languages: English, French, Portuguese, and Spanish. Of the 360 responses, 20% were from Small Island Developing States, 55% from other developing areas, and 25% from developed countries. The full report will be released in mid-2022. Based on the results of the

ODL assessment, DOOS will begin country-specific engagement to explore ways to help build deep-ocean observing capacity.

An Inspiring and Engaging Deep Ocean

A key goal of DOOS is the transfer of scientific knowledge to stakeholders including business, policy makers, and civil society to promote science-based decision making. It is critical that the work achieved by DOOS not only meets the needs of the scientific community but are translated so they may meet the needs of a society that increasingly relies on the services and resources of the deep ocean.

Improving the provision of deep-ocean information is a fundamental part of meeting Ocean Decade goals. The global societal need for deep observing to inform decision making at all levels is growing rapidly. This message is clear in the Sustainable Development Goals of the UN Agenda 2030 (Colglazier, 2015), the IPBES Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019), the UN Decade of Ocean Science (Claudet et al., 2020), and the recent IPCC Sixth Assessment Report (IPCC, 2022). Similarly, the ongoing UN negotiations for an international agreement on the conservation and sustainable use of marine biodiversity beyond national jurisdiction (Harden-Davies, 2017), the evolving CBD Post 2020 Global Biodiversity Framework, and developing regulations for mining of seafloor minerals by the International Seabed Authority (Jaeckel, 2019; Levin et al., 2020) emphasize this need.

DOOS is uniquely positioned to bring about the integrated understanding of the deep ocean that will be required to address these national and international challenges and to build a new generation of leadership in deep-ocean observation and management. In addition to DOOS' continued efforts through the Ocean Decade, DOOS seeks to directly connect with regulators, managers, and policy makers about advances in the deep sea. These efforts include interacting with representatives of UN agencies that have oversight over specific ocean sectors (e.g., fisheries, biodiversity, climate, shipping and pollution, mining, science) and working to form a policy liaison team that can inform on international data needs, new visualizations, policy briefs, and other products.

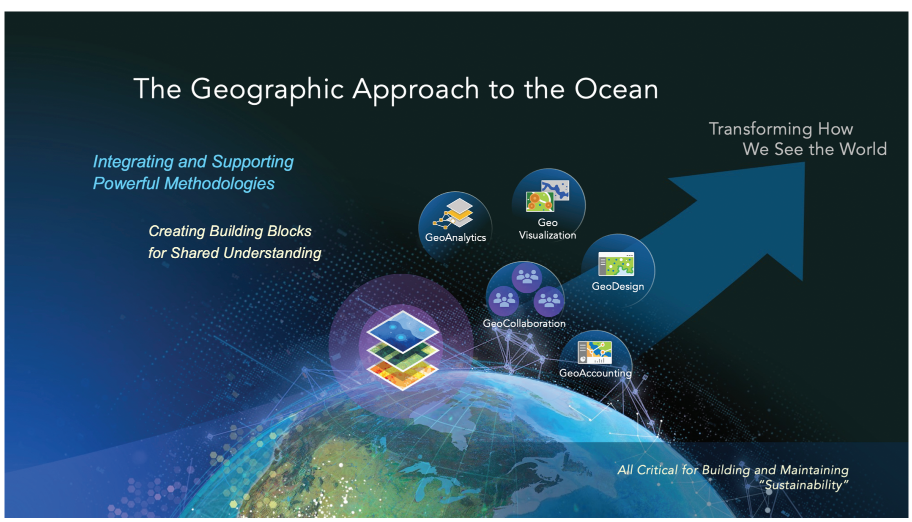
Additionally, through a partnership with the Environmental Systems Research Institute (Esri), DOOS will be taking the "geographic approach" to translate deep-ocean science to stakeholders and end users. Such an approach is a way of thinking and problem solving that integrates spatial data science and information into how we explore, designate, understand, manage, and communicate about the ocean (Esri, 2021). This approach integrates and supports powerful methodologies such as geoanalytics, for creating insight and understanding; geovisualization, through maps and other types of visualization for communicating the content and the context of our world; geodesign, designing sustainable and inclusive futures; and geocollaboration, engaging the entire community (Figure 5). These efforts will serve to support outputs from other DOOS initiatives as well as other key issues within the deep-ocean community and seek to reach a diverse set of stakeholders. The resulting data visualizations, maps, and StoryMaps will be openly hosted on the DOOS ArcGIS Hub as a community resource.

Through Decade and Beyond to the Next Generation

In the grand scheme of ocean history, a decade is a flash, an eighth of

FIGURE 5

A diagram illustrating the geographic approach to the sciences, as employed in DOOS, including the leveraging of geoanalytics, geovisualization, geodesign, and geocollaboration toward ultimate decision-making and action. Image provided courtesy of Esri.



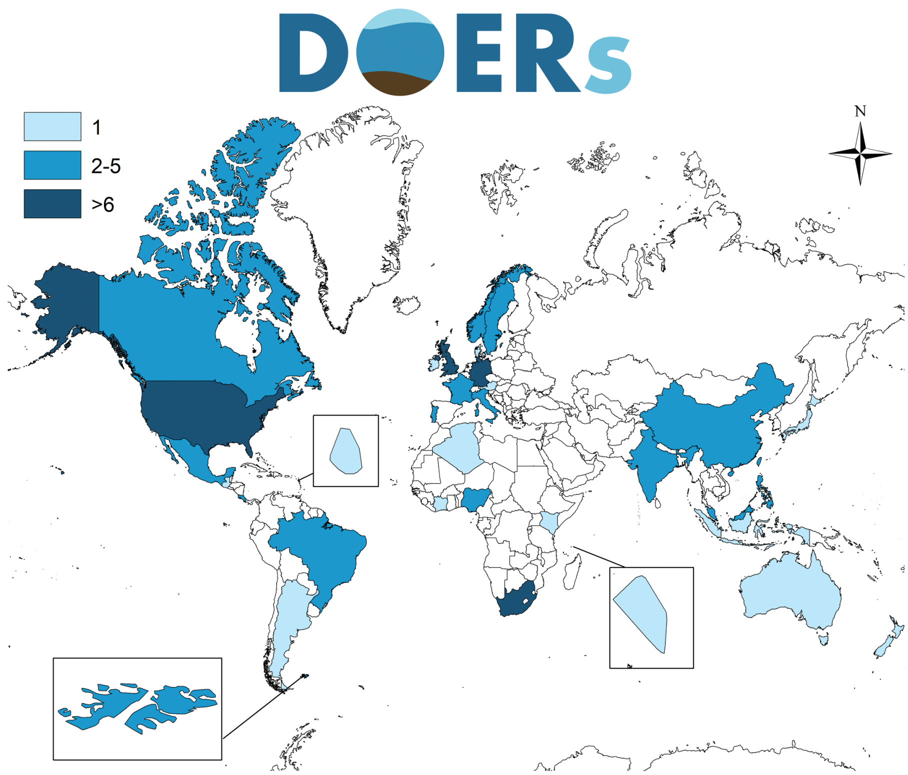
an average human lifetime, destined to pass quickly as we work to achieve the ambitions outlined above. The DOOS legacy of a well-connected, technically proficient, and collegial deep-ocean observing community that is highly inclusive of all types of people, from all countries of the world, and that can communicate with and meet the needs of multitude of deep-ocean stakeholders, must last much longer. Key to this legacy is the support and development of the next generation of deep-ocean observing leaders and practitioners.

To position the global deep-ocean community for success beyond the decade, DOOS has very purposefully created an organizational structure with a core focus on supporting a cohort of ECRs in meaningful leadership positions. These ECRs create a cohort with multi-disciplinary expertise across physics, biology/ecosystems, biogeochemistry, modeling, technology development, and data science. ECRs are supported by mentors at their home institutions, peer-to-peer mentoring, integration across DOOS' networks, and direct engagement with the project director. They are provided the space to push forward their own ideas, take risks, make mistakes, be uncertain, and then rejoice in and receive full credit for their successes. In this way, DOOS has created a new model for how to empower, elevate, and train early career researchers to be the leaders we need for the ocean we want.

Additionally, to train an extended cohort of ECRs from around the world, DOOS has created the DOERs professional development program. DOERs is designed to bring together ECRs from across and beyond our network of networks and include members from underserved communities, including developing countries, indigenous communities, women, and underrepresented minorities. Key goals of the program are to (1) advocate for and raise the profile of deep-sea ECRs; (2) provide transferable skills in the areas of networking, collaboration, and outreach as well as basic literacy in scientific data use and management; and (3) cement inclusion of these ECRs as future leaders of the scientific community. The DOERs program is currently made up of 120 ECRs that span across the globe; two thirds are from outside of the United States and, of those, 33 are from developing countries or small island nations (Figure 6).

FIGURE 6

Geographic distribution of participants in the DOERs professional development program. Map was created by Lauren Haygood, Oklahoma State University, DOERs participant.



Concluding Remarks

The Ocean Decade provides a unique opportunity to bring together the global deep-ocean community to focus their efforts on ocean science for sustainable development. Within the GOOS, the deep ocean is the most logistically challenging and costly to observe and requires dedicated efforts to coordinate the deep-ocean community to make progress. DOOS aims to break down barriers and build partnerships across countries, networks, disciplines, and communities to seek collective solutions to global deep-sea challenges like climate change, biodiversity loss, and resource exploitation. DOOS stands on the principles of open data sharing, communication, and the promotion and development of ECRs to become future leaders in deep-sea observing. DOOS operates through a series of working groups that each addresses a global deep-sea challenge. These working groups were designed with community input to determine priority actions, leverage existing research efforts and resources, and address defined challenges and gaps together. In order to successfully accomplish the goals of the Ocean Decade and make headway on the global challenges outlined in this paper, the deep-ocean community cannot remain siloed, isolated, and with efforts divided across countries. As the deep-ocean community moves through the decade, success will be measured by building capacity, tools, and teams that are delivering information designed to meet needs of sustainability and conservation, while maintaining key ecosystem service and resource supplies. A truly successful Ocean Decade for the deep-sea community will also be one that changes the way we think about science and the way we think about and work with each other. DOOS is aligned to provide that collaborative interface, to build a cohesive network of networks, and to accelerate deep-ocean research through the decade and beyond.

Acknowledgments

Funding for the DOOS comes from the U.S. National Science Foundation AccelNet program, Award #2114717.

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