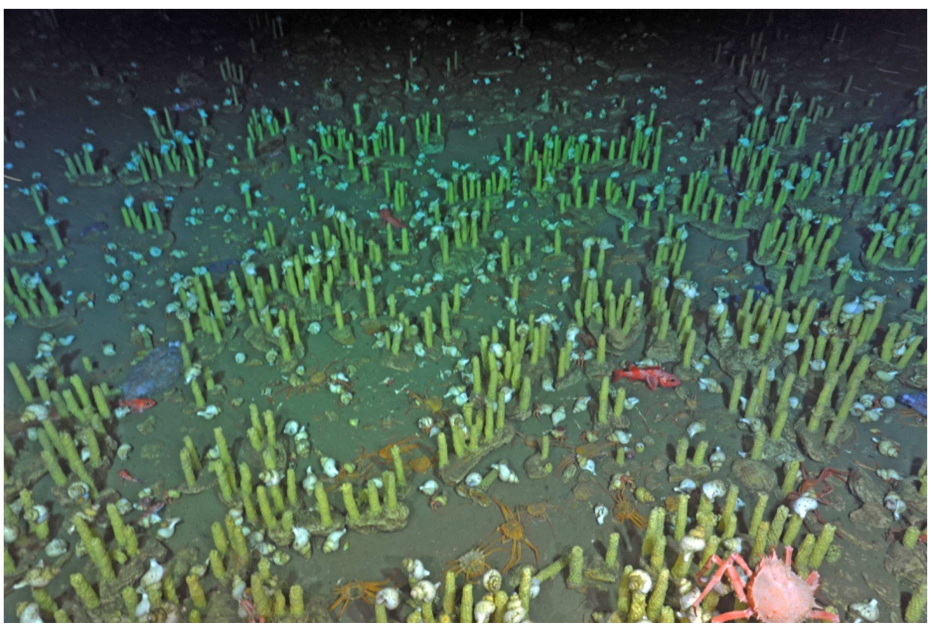
DEEP OCEAN OBSERVING STRATEGY

Science and Implementation Guide



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Authors

Lead Authors: Levin, L.[1], Ruhl, H.[2], Heimbach, P.[3], McCurdy, A.[4], and Smith, L.[5]

Supporting Authors: Baumann-Pickering, S.[1], Carreiro-Silva, M.[6], Gjerde, K.[7], Howe, B.[8], Janssen, F.[9], Katsumata, K.[10], Kelley, D.[11], Le Bris, N.[12], Smith, C.[13], Snelgrove, P.[14], Song, S.[15], Soule, A.[16], Stocks, K.[1], Rome, N.[17], Venkatesan, R.[18], Weller, R. [16]

Editorial Support: Desai, K.[17], Menodoza, G.[1]

[1]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA
[2]National Oceanography Centre, Southampton, United Kingdom
[3]University of Texas at Austin, Austin, TX, USA
[4]University Corporation for Atmospheric Research, Naples, FL, USA
[5]Your Ocean Consulting, LLC, Knoxville, TN, USA
[6]Centro OKEANOS, Universidade dos Açores, Horta, Portugal
[7]IUCN Global Marine and Polar Programme Advisor, Middlebury Institute of International Studies in Monterey, California, Cambridge, MA, USA
[8]University of Hawaii at Manoa, Honolulu, HI, USA
[9]Deep Sea Ecology and Technology group, Alfred Wegener Institut Helmholtz Zentrum für Polar und Meeresforschung, Bremerhaven, Germany
[10]Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan
[11]University of Washington, Seattle, WA, USA
[12]Observatoire Océanologique de Banyuls, Sorbonne Université, Banyuls-sur-Mer, France
[13]University of Hawaii, Honolulu, HI, USA
[14]Memorial University, St. John's, NL, Canada
[15]Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China
[16]Woods Hole Oceanographic Institution, Woods Hole, MA USA
[17]Consortium for Ocean Leadership, Washington, DC
[18]National Institute of Ocean Technology, Chennai, India

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EXECUTIVE SUMMARY

The deep ocean is a dynamic, yet poorly explored system that provides critical climate regulation, hosts a wealth of hydrocarbon, mineral, and genetic resources, and represents a vast repository for biodiversity. The sustainability of the deep ocean and its services, however, relies on scientific understanding. **The Deep Ocean Observing Strategy (DOOS) envisions a globally integrated network of systems that can observe the deep ocean effectively in support of strong science, policy and planning for sustainable oceans.**

Who is DOOS? DOOS represents a coalition of international deep-ocean stakeholders from science, management, government, and industry for waters within and beyond national jurisdiction. Ocean observers, data managers, and data users are all encouraged to participate in guiding DOOS. Researchers, educators, regulators, policy makers, NGOs, IGOs, and the public are among the beneficiaries of DOOS.

What is the scientific focus? DOOS focuses on ocean depths below the main thermocline (> 2000 m), with additional attention to shallower processes and mechanisms that are poorly sampled below the photic zone (> 200 m) that influence the deeper depths. Three overarching science goals provide the basis for DOOS: (i) understand global deep and bottom water formation rates, their variability, and the time scales of their global property changes while assessing global heat, salt, and freshwater budget dynamics; (ii) document deep ocean tracer transport and ventilation processes and assess their impact on ocean biogeochemical processes, both on the seafloor and in the water column; and (iii) understand marine deep-sea biodiversity and ecosystem services in light of human-induced and natural changes. Understanding these processes will also contribute to national and global sustainability efforts and climate forecasting and policy decisions.

What are the main objectives?

1. Identify Essential Ocean Variables (EOVs) and evolve their specifications to fully consider deep-ocean perspectives across physical, biogeochemical, biological, and ecological variables over the next decade. This includes adding the deep ocean perspective to existing GOOS EOVs and adding additional deep ocean EOVs. The development of these EOVs will improve understanding of the state of the deep ocean, characterize existing conditions, and quantify its response to climate variability and human disturbance.
2. Design and evaluate observing systems and oversee demonstration projects and process studies. Demonstration projects and process studies will provide a blueprint for global deep-ocean observation technology readiness and deep-ocean data findability (discovery), accessibility, interoperability, and reusability (FAIR). They will help mature nascent platforms and sensors and work to integrate observing efforts across disciplines. Demonstration projects are currently proposed for the Clarion Clipperton Fracture Zone, the Northeast Pacific, and the Azores Archipelago.
3. Serve as a communication hub for a broad spectrum of stakeholders in the deep-ocean science, data, and information user community. Specifically, these efforts focus on facilitating cross-disciplinary information transfer among physicists, biogeochemists, biologists, engineers, technology experts, data managers, law and policy specialists, and social scientists addressing the deep ocean.

4. Provide an avenue through which the deep ocean research community and the data they produce can reach policy makers and inform policy decisions.

What is DOOS's relation to GOOS and other networks? The DOOS Project was launched as a GOOS Project to develop a strategy for sustained observation of the deep ocean. DOOS aims at closing a substantial gap in global ocean observing that has historically been underemphasized, due largely to the difficulty of observation in the deep ocean. While DOOS is managed independently of GOOS, their activities and priorities are aligned through utilization of the Framework for Ocean Observing (FOO) as a guiding set of central processes and principles – e.g. the concept of EOVs and the development of a fit-for-purpose observing system through the maturation of requirements, technologies, and information, all driven by science and societal need.

DOOS will engage with existing deep-ocean scientific networks, large deep-ocean observing programs, and seafloor observatories, including: the Deep Ocean Stewardship Initiative (DOSI), the International network for scientific investigation of deep-sea ecosystems (INDEEP) and the Southern Ocean Observation System (SOOS). Some examples of collaborations include:

- Contribution to the Group on Earth Observations (GEO) and the GEO System of Systems (GEOSS) to deliver environmental data and decision-support tools to academic, industry sector, and government end users.
- Development of protocols and standards for collection of biodiversity observations in the deep ocean that can be incorporated into the Marine Biodiversity Observation Network (MBON) of the GEO Biodiversity Observation Network (GEO BON) and GEO Blue Planet.
- Collaboration with the Ocean Best Practices (OBP) working group of the Intergovernmental Oceanographic Commission (IOC) to store standards and methods.
- Joint voluntary commitment (with DOSI and INDEEP) to Sustainable Development Goal 14 to build global scientific capacity to address SDG 14 targets as they relate to the deep ocean.

DOOS is conducting and will maintain an inventory that seeks to assess the status of deep-ocean observing with respect to water depths, platforms, sensors, variables measured, and temporal and geographic coverage. It is designed to inform the development of DOOS by identifying potential partners and providing a common statement of requirements, as well as an initial strategy for sustained global deep ocean observations.

Ultimately, DOOS strives to unlock critical knowledge about the deep ocean to deliver scientific and societal benefits for the future. Emerging technology advances, changing resource pressures, and climate change result in expanded relevance and need for deep-ocean observations. International commitments to end poverty, protect the planet, and ensure prosperity for all, as embodied in the UN's 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), are driving demands for increased science to inform decision making. The deep ocean has a fundamental role to play in these decisions. DOOS anticipates facilitating input from deep-ocean observations to the UNFCCC and Paris agreement, the IPCC, the Decade of Ocean Science for Sustainable Development, the UN Regular Process (World Ocean Assessment), the International Seabed Authority, the Food and Agriculture Organization, the International Maritime Organization, the BBNJ treaty negotiations, and regional entities. Additionally, DOOS seeks to contribute to capacity building efforts with developing states and early career scientists to strengthen the deep-ocean observing community. The next century promises expanding uses and new stakeholders for deep-ocean observations.

I. DEEP OCEAN OBSERVING: INTRODUCTION AND RATIONALE

A. DOOS VISION AND OBJECTIVES

The vision of the DOOS Project is to help develop an enduring, globally integrated network of systems that can effectively observe the deep ocean and accelerate our understanding of changing conditions in order to support strong science, policy, and planning for sustainable oceans. DOOS focuses on the area below the main thermocline (> 2000 m), with additional attention to shallower processes and mechanisms that are poorly sampled below the photic zone (> 200 m) that influence the deeper depths.

Setting the stage for an emerging and distributed deep-ocean observation system, DOOS addresses 1) societal issues and scientific questions driving the demand for deep-ocean observations, 2) Essential Ocean Variables (EOVs) needed to address these, 3) currently available observing technologies, including needs for further development, and 4) guiding principles for the provision of data and products.

Box 1. SCIENCE QUESTIONS AS DRIVERS OF DEEP-OCEAN OBSERVING

1. What is the role of the deep-ocean in the Earth's energy imbalance and land/sea water redistribution on annual to multi-decadal time scales? This includes closing the heat and freshwater budget, the warming and freshening of the deep ocean, and their contribution to sea level change.

2. How are natural and anthropogenic variations in climate connected to the global overturning circulation and its variability? This includes variations in deep and bottom water formation rates and water properties, circulation and deep ocean mixing, exothermal heating, and impacts on deep-sea ecology.

3. How does deep pelagic ecology respond to natural variation and multiple climate change stressors, including warming, deoxygenation, acidification, changes in biological production, as well as industrial activities?

4. How might natural and anthropogenic variations in climate influence the function of the solubility and biological carbon pumps, continental slope, nepheloid layer transport and the sequestering of carbon in the deep ocean, and the supply of organic carbon food supplies to deep-sea communities?

5. What drives observed variation in seafloor fluxes of heat, nutrients, tracers, oxygen and different carbon pools? How are these quantities connected to larger-scale ocean circulation? This includes long-term links between seafloor fluxes and greater oceanic physical and biogeochemical processes.

6. How might natural and anthropogenic variations in climate and resource industry activities influence the functional importance of animals and microbes in the deep sea and the seafloor? What environmental variations do they experience in space and time? This includes consideration of benthic storms and currents, fluctuations in turbidity, T, pH, O2, and POC flux. This will improve spatial planning and impact assessment for seabed mining, bottom trawling and oil and gas extraction.

DOOS has as a primary objective to improve understanding of the state of the deep ocean by identifying new, or improving specification of existing EOVs across the physics, biogeochemistry, biology and ecology disciplines, in order to characterize existing conditions and quantify the response to climate variability and human disturbance.

DOOS will also identify approaches to address key scientific questions and societal needs, identify knowledge gaps, and, where appropriate, design and evaluate observing systems, demonstration projects, and process studies.

In addition to EOVs and demonstration projects, DOOS seeks to become a central nexus for the deep-ocean observing community. In this capacity, DOOS will act as a communication hub for the community to connect organizations across the broad spectrum of deep-ocean stakeholders including researchers, industry, and management. In this way DOOS could also serve as a facilitator for collaborations wherein researchers can acquire access to data collected by industry, or researchers can better leverage the efforts of other researchers by taking part in scheduled cruises, etc. DOOS can also provide an avenue through which the deep-ocean research community can reach policy makers, contributing information needed to enable policy decisions.

B. DEVELOPMENT OF DOOS

1. HISTORICAL DEVELOPMENT

Initial DOOS discussions and preparation began in 2010 at a preliminary deep-ocean meeting held in Pasadena, California. This was followed by the release of a DOOS Consultative Draft Report in 2013 that evolved through 2015, when a leadership team was formed involving the Scripps Institution of Oceanography, the University Corporation for Atmospheric Research (UCAR), and the Consortium for Ocean Leadership (COL). In 2016, this team sought community input on the DOOS Consultative Draft[1], conducted a deep-ocean observing inventory[2], and formed a workshop planning committee[3] to organize an initial scoping workshop (Figure 1).

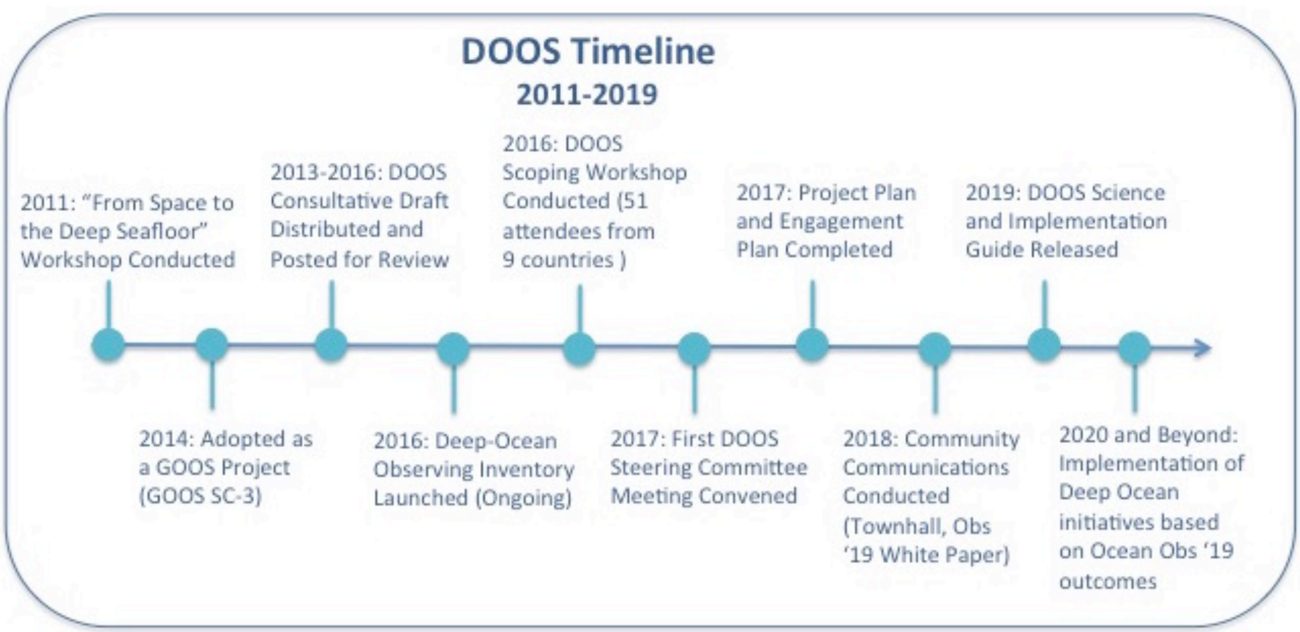

Figure 1. *Timeline of DOOS development*

[1] http://www.deepoceanobserving.org/reports/consultative-report/
[2] http://www.deepoceanobserving.org/activities/deep-ocean-inventory/
[3] Initial planning committee members were: Antje Boetius, Albert Fischer, Patrick Heimbach, Greg Johnson, Lisa Levin (Chair), Henry Ruhl, Bernadette Sloyan, Sun Song, Toste Tanhua, and Rik Wanninkhof

The 3-day DOOS Community Workshop was held at Scripps Institution of Oceanography during December 2016. It brought together 51 participants from 9 countries to identify societal and scientific drivers for DOOS and define project elements and key scientific questions that should be addressed with deep observations. Discussions at the workshop focused on defining the scope and objectives of DOOS including: what measurements are needed in the deep ocean, observing systems that meet these scientific and functional requirements, gaps, inefficiencies and vulnerabilities, and the status of deep observing technology (platforms, sensors, and samplers). Participants reviewed and prioritized existing and potential EOVs in deep waters, evaluated logistical requirements for the implementation of DOOS and delivery of data, derived products and information, and discussed collaborators, strategies, and funding.

The workshop culminated in preparation of a Scoping Workshop Report[4], development of Terms of Reference, and establishment of a DOOS Steering Committee (DOOS SC) consisting of 17 members from 8 countries and 13 institutions. Four task teams[5] were formed to address deep Physics EOVs, Biogeochemistry EOVs, and Biology and Ecosystem EOVs, as well as Data and Cyberinfrastructure. Additional subcommittees were created to consider capacity building, demonstration projects, engagement of the UN, and the solid Earth community. Development of a 'Large Program' subcommittee to liaise with existing deep-ocean observing programs is under consideration.

Box 2. DOOS STEERING COMMITTEE MEMBERS AND AFFILIATIONS

CO-CHAIRS
Lisa Levin, USA, Scripps Institution of Oceanography, University of California, San Diego
Patrick Heimbach, USA, University of Texas at Austin
Henry Ruhl, UK, National Oceanography Centre

MEMBERS:
Simone Baumann-Pickering, USA, Scripps Institution of Oceanography
Kristina Gjerde, USA, International Union for Conservation of Nature, Global Marine and Polar Programme
Bruce Howe, USA, University of Hawaii at Manoa
Felix Janssen, Germany, Alfred-Wegner Institute
Katsuro Katsumata, Japan, Japan Agency for Marine-Earth Science and Technology
Deb Kelley, USA, University of Washington
Nadine LeBris, France, Sorbonne Universités
Craig Smith, USA, University of Hawaii at Manoa
Paul Snelgrove, Canada, Memorial University
Sun Song, China, Institute of Oceanology, Chinese Academy of Sciences
Adam Soule, USA, Woods Hole Oceanographic Institution
Karen Stocks, USA, Scripps Institution of Oceanography
R. Venkatesan, India, National Institute of Ocean Technology Ministry of Earth Science
Bob Weller, USA, Woods Hole Oceanographic Institution

In April 2017, the newly established DOOS SC met by conference call, and then met again in September 2017[6] in person in Washington DC. The goals of these initial meetings were to further plan for DOOS EOV development,

[4] http://www.deepoceanobserving.org/reports/dec-2016-workshop-report/
[5] http://deepoceanobserving.org/about/project-structure/
[6] http://www.deepoceanobserving.org/reports/

creation of demonstration projects, preparation of this Science and Implementation Guide (SIG), and participation in the OceanObs '19 Conference. A DOOS Townhall was held at the 2018 AGU Ocean Sciences Meeting (Portland, OR)[7] to broaden engagement of the scientific community. A survey was distributed to participants at the Townhall to gauge forms of interest and generate input to this Report.

2. PROJECT MANAGEMENT AND ENGAGEMENT

DOOS functions in accordance with a Project Management Plan (PMP). The PMP supports the enhancement of the efficiency, effectiveness, robustness, and sustainability of the Project, as well as assists with improved governance and coordination designed to facilitate and embrace contributions from multiple agencies and countries. The structure of the DOOS project consists of a Steering Committee to oversee scientific and programmatic objectives, technology and data evaluation, identification of societal needs and advocacy, and facilitation of demonstration projects. DOOS employs a 'lite' Project Management model encompassing a Distributed Project Office (DPO) with a focus on coordination and oversight of project resources, as well as facilitation of scientific and technical activities. This activity is conducted through the management and completion of a series of 'Tracked Actions' that are agreed to periodically by the Project SC and leadership. The Project reports episodically to the GOOS Steering Committee.

As a guiding document, the PMP addresses an Engagement Plan (Figure 2) that identifies and describes a concerted engagement methodology. The DOOS Engagement Plan is a mechanism through which the Project identifies a list of activities leading to sustained global deep-ocean observation for the next 10-50 years. The Engagement Plan helps collect and track information to guide the project toward further alignment with successful observation and advocacy best-practices (Figure 2B, helping to drive long-term sustainability and observations that are fit-for-purpose. The goal is the creation of a strategy that will lead to an observing system that meets societal needs for policy, regulation, and advocacy, based on sound scientific understanding.

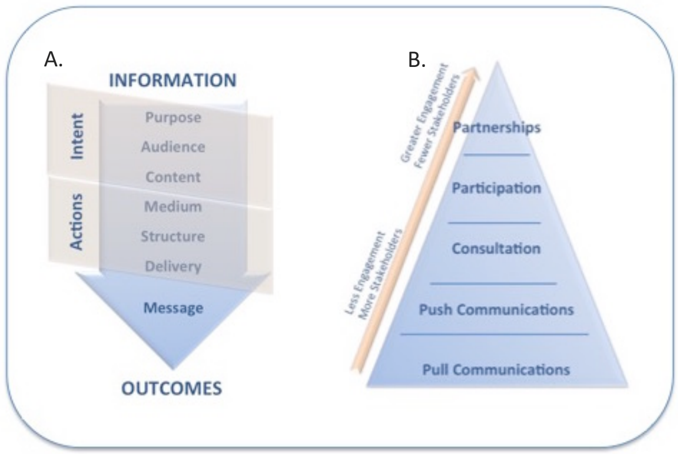

Figure 2. *Project management efforts. (A) Information pathways (B) Engagement categories).*

C. SOCIETAL MOTIVATION FOR DEEP-OCEAN OBSERVING

Observation of the ocean has long been devoted to understanding and managing risk related to human activities. Examples include the need to anticipate extreme events with destructive power such as hurricanes, or disruptive climate anomalies such as El Niño that affect ocean ecosystems and livelihoods, or utilizing ocean observations to protect shipping, shorelines, and coastal infrastructure. However, emerging observational needs today go

[7] http://www.deepoceanobserving.org/2018/01/18/ocean-sciences-meeting-2018-doos-town-hall/

beyond 'event detection' and include a full inventory of human and climate stressors (e.g., ocean deoxygenation and acidification), ecological risk assessment, and an understanding of how marine resources will be affected by these changes. Moreover, there is a need to understand change in the context of multiple stressors and cumulative impacts, including those of humans (Figure 3), based on co-located simultaneous observations. Often observation value expands beyond original intent. For example, the implementation of sustained geophysical observation networks in the deep ocean and on the seafloor was initially intended to develop early geo-hazard warning but now also sheds light on biogeochemical and ecological phenomenaUtilizing ocean observing as a tool to forecast processes from sub-seasonal to interannual timescales has intensified in recent decades with the advent of mooring arrays, Argo floats, cabled observatories, and other technologies.

Today human activities associated with the extraction of energy and living resources routinely extend into deep waters, and new deep-sea industries such as seabed mining, gas hydrate extraction and bioprospecting are on the horizon (Figure 3, Ramirez-Llodra et al. 2011). Natural resource and other maritime industries regularly collect large volumes of data that are not yet shared using standards and practices of the GOOS framework. Waste disposal, plastic accumulation and chemical contaminants also impose new information needs. Environmental management in the face of growing industrialization of the deep ocean requires basic knowledge, new strategies and novel tools (Mengerink et al. 2014). Deep-ocean biodiversity loss and climate-induced regime shifts are occurring in some places and anticipated in others (Levin and Le Bris 2015). The protection of deep-ocean infrastructure, and the science underlying protection of the marine environment require an increasing quantity and complexity of deep-ocean observations sampled more broadly in space and time than ever before.

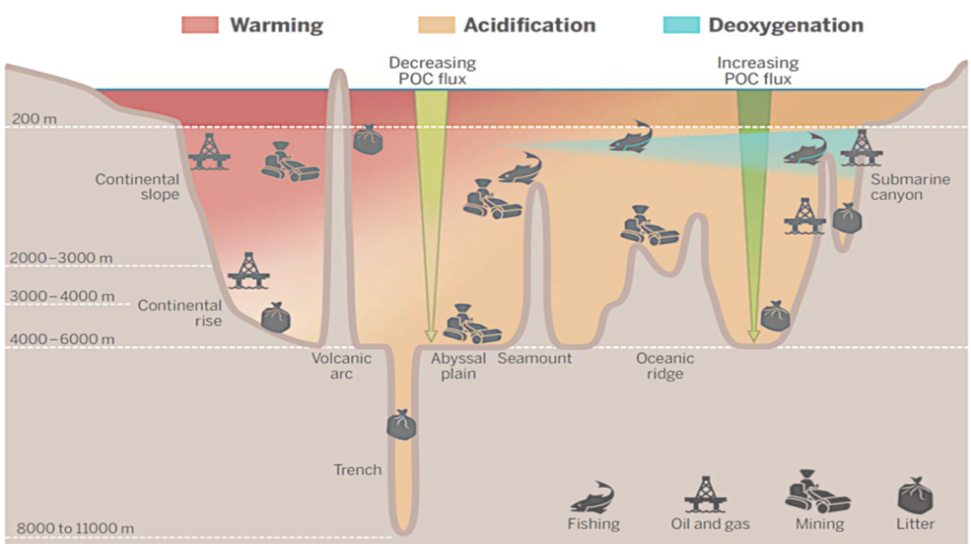

Figure 3. *Climate-induced changes in temperature, pH and oxygenation are superimposed on disturbance from human resource extraction and debris accumulation. From Levin and LeBris 2015.*

Fundamental science provides a rational framework for extrapolating knowledge beyond existing specific observations, helping to address information gaps and societal needs. This can bridge scales between individual observations to those of management and planetary processes. As an example, the capacity of deep-sea communities to face major disturbance has been studied through multi-year observations following a massive volcanic eruption (a natural disturbance analog). The results have been used to identify key processes and variables influencing recolonization and recovery, and the importance of the interconnection between distant populations.

As the deep ocean plays a critical role in climate variability and change, new physical, biogeochemical and biological observations in deep waters will underpin and improve our ability to predict future change and to develop possible adaptive strategies for society to cope with climate change. As conservation strategies for deep-sea ecosystems develop (e.g. marine protected areas), the need for better spatial and temporal monitoring of stressors (warming, acidification, deoxygenation) resulting from anthropogenic CO_2 accumulation in the atmosphere becomes an international science and societal priority. The societal relevance and need for ecosystem research and monitoring at great depths are well recognized (e.g., Danovaro et al. 2017) and a diverse set of technical solutions are emerging to address this need (Levin et al. in press).

The next century promises expanding uses and new stakeholders for ocean observational data. Sustainability is a growing refrain for both existing and new ocean industries. Economic viability, financial risk and ecological impact assessment, and conservation actions all will depend on improved ocean observing and monitoring. Ocean industries can improve the sharing of data they collect to understand the environments in which they operate, adding transparency to their operation and providing information to areas of the sea that are not readily visible. Waste, contaminants, sound, and light will need to take their place among more traditional parameters in our future observing efforts. As the likelihood grows that climate mitigation will require an expanded toolkit (e.g., ocean geoengineering), ocean observing will become even more critical. Emerging technology advances, changing natural resource pressures, and the context of global change are undoubtedly creating new opportunities for deep-ocean observations.

D. SCIENCE CHALLENGES

1. PHYSICAL CLIMATE CHALLENGES

Deep ocean physics science challenges include deep ocean ventilation and circulation and its variability, meridional overturning circulation, deep ocean warming and freshening, impact on patterns of sea level rise, and geothermal heating. These challenges not only reflect the baseline need to better characterize these processes in the deep ocean, but also to do so in the context of a changing climate.

The most fundamental quantity to characterize global climate change is the heat inventory in the Earth system. The ocean absorbs more than 90% of the anthropogenic heat imbalance (IPCC AR5). As a result of complicated ocean circulation, this added heat is redistributed vertically and horizontally across the globe. Our knowledge of how the heat is distributed, however, is largely biased towards the upper ocean as most of our observations are focused on shallow depths. For example, there are roughly 261,000 temperature profiles reaching 2000 m, compared with roughly 62,000 reaching 4000 m (Boyer et al. 2013, Abraham et al. 2013). As such, though it is established that sea water above 2000 m is warming at a statistically significant rate (Gleckler et al. 2016), the scarcity of data below 4000 m has made it difficult to establish a clear trend. For example, some regions of the Southern Ocean are exhibiting statistically significant warming (Purkey and Johnson 2010), in contrast, other regions of the deep ocean, such as parts of the Atlantic Ocean, are exhibiting slight cooling. This may reflect the imprint in the deep ocean of centennial to millennial scale surface climate anomalies in the parts of the Pacific Ocean (Wunsch and Heimbach 2014, Palmer et al. 2017). Currently, data at those depths can be collected from deep moorings, cabled observatories, and ship hydrography. Emerging new technologies including deep Argo floats, expendable deep moorings, landers, and smart cable observatories promise further expansion of deep-ocean observations.

The degree to which the heat, salt and freshwater budgets in the ocean can be closed determines how well the anthropogenic impact on the coupled atmosphere-ocean-cryosphere system can be evaluated. For example, heat, salt and freshwater inventories reflect exchanges with surface-atmosphere, land-ocean, and water column-seafloor boundaries and their distribution changes by advection (i.e., ocean currents) and diffusion (i.e., ocean turbulence). Ocean currents are steered by bottom topography that often limit important water mass exchange processes geographically. Deep mooring and ship observations can be concentrated in these and other areas of important fluxes. In addition to time series measurements at these flux choke points, these platforms can be used to measure the interaction between the solid ocean bottom and the fluid ocean. Complete mapping of the seabed, subduction zones, mid-ocean ridges, and hot vents (e.g., Mayer et al. 2018) would facilitate ocean budgeting studies.

Because of the eclectic nature of ocean observing across the globe, formal synthesis frameworks involving models and inverse methods provide powerful tools for developing optimal estimates of the full ocean state (e.g., Bell et al. 2015, Martin et al. 2015, Stammer et al. 2016), but associated uncertainties remain difficult to quantify (Wunsch 2016, 2018).

2. BIOGEOCHEMISTRY CHALLENGES

The deep ocean plays a critical role in global biogeochemical cycles. The ocean produces about half the oxygen we breathe and absorbs about one third of the anthropogenic CO_2 emissions (Sabine et al. 2004, Khatiwala et al. 2009, Le Quéré et al. 2015). Most of the current research questions regarding biogeochemistry of the deep ocean are concerned with its ability to store carbon dioxide from the atmosphere, mitigating anthropogenic carbon emissions.

Deep ocean biogeochemistry challenges include: the oceanic carbon inventory, ocean acidification, the biological carbon pump, deoxygenation, and nutrient dynamics. Carbon dioxide storage takes place either by direct uptake via the ocean surface and physical transport to the ocean interior, or by uptake in biomass that is exported to depth for long-term residence in the deep-water column or ultimate sequestration in deep ocean sedimentary deposits. As such, changes in surface water productivity, deep ocean respiration and remineralization, as well as circulation and mixing of the deep ocean can affect carbon cycling, as well as oxygen and nutrient levels. The uptake of inorganic and organic carbon leads to changes in ocean chemistry, i.e., deep ocean acidification and oxygen inventories, which in turn affect biogeochemical processes, marine organisms, and their functions. The tight coupling between biogeochemical properties, ocean circulation (advection and diffusion), and life in deep waters and at the seafloor, calls for joint biogeochemical, physical and biology/ecosystem observations.

Ocean acidification is ongoing and global climate models predict that intermediate and deep waters will substantially acidify by the end of this century (Bopp et al. 2013). Impacts of acidification may be amplified due to ecological responses to these changes in the marine carbon system, such as by an increase in nutrient recycling and decrease in organic carbon export through the water column. Changes in carbon inventory and fluxes in the deep ocean are typically significantly slower than in the upper water column. However, in part due to its vast volume, even these slight changes can have an appreciable effect on global biogeochemical mass balances and the storage of anthropogenic carbon. Improvement in the quantification of biogeochemical changes in the deep ocean is imperative to understand the global carbon cycle, particularly over centennial and longer timescales.

The long term trends in deep water contribution to the oceanic carbon inventory with an emphasis on the increase of anthropogenic carbon and the associated effects on the carbonate system and ocean acidification need to be monitored by intensified sampling of the deep-ocean for carbonate system parameters (Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA), pH), and stable carbon isotopes. To understand transport and redistribution of inorganic carbon in the deep ocean, transport and mixing processes need to be addressed, e.g., by means of natural and man-made tracers and physical observations of current and turbulence regimes. Transient tracers (e.g., CFCs and SF6, tritium, 3He, 13C, 14C and Neodynium) are key for studies of ocean ventilation and its time scales.

The ocean carbonate system, solubility pump, and biological carbon pump play interlinked roles and regulate many aspects of ocean ecosystem function, services, and benefits to society (e.g. oxygen to breath and food security). Particulate Organic Matter (POM) is the main source of energy to most deep-sea life (see next section) and, when buried in the seafloor, also represents a relevant carbon sink at geological time scales. POM export to the deep ocean shows pronounced regional differences and a strong seasonal and inter-annual variability. Understanding this variability is critical to determining the portion of POM that is ultimately remineralized or buried in sediments. In addition, the deep ocean receives vast amounts of organic material as Dissolved Organic Matter (DOM) which, similar to POM, can contribute significantly to the biological pump by removing carbon from the atmosphere and transferring it to deep waters (e.g., Hansell et al. 2009).

Sustained regional observations both with traditional moored particle traps as well as novel instrumentation for high resolution observations (e.g., particle cameras, optical sensors) deployed with novel platforms (e.g., Biogeochemical (BGC) Argo and neutrally buoyant, drifting particle traps) can characterize the spatial, seasonal, and inter-annual variability in bathypelagic flux characteristics of POM. Time series observations of detritus deposition and respiration rates at the seafloor by means of moored or mobile platforms can help researchers constrain the supply and fate of organic matter at the bottom of the oceans.

Deep-water oxygenation and nutrient pools are key factors determining ocean health and productivity. Oxygen is fundamental to most life in the ocean, thus understanding the nature and causes of oxygen variation is necessary to predict biological responses to climate change. Ocean warming-induced changes in solubility, stratification, ventilation, wind-driven local hydrodynamic forces, and respiration are leading to global declines in oxygen (Keeling et al. 2010, Schmidko et al. 2017, Levin 2018). Oxygen is highly sensitive to changes in biomass and respiration and hence is directly connected to the export of organic material to the ocean interior (e.g., Joos et al., 2003). There is also strong evidence that open ocean nutrient availability and its ecological consequences (e.g., regarding productivity, primary producer communities, and export fluxes) are under the influence of global change (Pörtner et al. 2014). The involved sources, sinks, and processes of these nutrient cycles are complex and interlinked and require both more observation time series and process studies (e.g. Karl 2002, Duce et al. 2008, Zehr et al. 2011). Although anthropogenic activities (e.g., fossil fuel combustion and fertilizer production) are increasing the input of reactive nitrogen to the ocean, the concurrent decrease in nitrogen via denitrification could potentially lead to a net reduction of oceanic nitrogen with potentially strong implications for oceanic productivity (Galloway et al. 2004)

Long-term observations are needed to assess variability in deep-water biogeochemical conditions related to oxygen and nutrients, including their physical and ecological drivers across seasonal to decadal time scales and the longer-term secular trends in the deep ocean. Geographic emphasis on regions undergoing major change (e.g., the expanding oxygen minimum zones in the East Pacific, Southern Oceans, and eastern North Pacific, Stramma et al. 2012, Keeling et al. 2010) and other regions reaching oxygen thresholds that affect ecosystem services (e.g., fisheries) will provide the mechanistic understanding needed to properly model future oxygen changes and biological responses. New technologies (e.g., optical and Lab-on-a-chip sensors and BGC Argo floats) offer opportunities for high-resolution nutrient measurements to better resolve deep ocean nutrient pools and their dynamics in order to address open ocean productivity and its changes, including feedback to the biological carbon pump.

Observations of seafloor fluid and gas fluxes are crucial to understand the total global budgets of elements and greenhouse gases. Methane, a particularly potent greenhouse gas is released into the ocean via hydrothermal emissions driven by volcanic activity or mantle-rock alteration, as well as from methane reservoirs and hydrates through the escape of gas, fluid, and mud extrusion. The flux of methane is sensitive to changes in the deep ocean, for example, deep-water warming enhances methane hydrate dissociation and effluxes from the seafloor. Changes in methane release can directly affect the nearby benthic ecosystems, specifically the high-biomass vent and seep communities that are fueled by methane oxidation. Additionally, methane dissociation and mud volcano eruptions can destabilize margin sediments and initiate debris and liquefied sand flows which may pose hazards to deep ocean infrastructure (e.g., oil and gas rigs, cables), positively feedback on hydrate dissociation, and possibly cause tsunamis. The impact of changes in methane release at the seafloor on atmospheric greenhouse gas concentrations is also insufficiently constrained.

3. BIODIVERSITY AND ECOSYSTEM CHALLENGES

Of the three ocean observing disciplines, Bio and Eco is the most in need of coordination and maturation, across the global ocean, including the deep-sea. As such, many of the drivers for observations, EOVs, and novel technology across this discipline focus on filling gaps in knowledge. For example, little is currently known about the relationships between deep-sea biodiversity, functional groups, and ecosystem functions. These gaps limit the capacity to assess the risks of ecosystem shifts associated with climate change impacts and to develop relevant monitoring strategies for environmental impact assessments of industrial disturbance of seafloor habitats. For example, the relatively rapid warming of cold abyssal regions could cause shifts in microbial rates, predator/prey interactions, species composition, functional groups, and ecosystem engineers with consequences for nutrient cycling and carbon remineralization or sequestration. Global-change stressors can affect deep ocean biodiversity and related food webs via multiple pathways - compounding local anthropogenic impacts, altering habitat suitability, and changing carbon flux to the deep sea.

Just as there is a knowledge gap related to the impacts of climate change in the deep sea, there is a gap in understanding the cumulative impact of multiple stressors. Of particular importance is the capacity for ecosystem resilience, in the context of climate change, after direct, local anthropogenic impacts such as fishing, dead zone extension, waste disposal, drilling, and extraction of minerals. For example, polymetallic nodule provinces, seamounts, or hydrothermal vent areas targeted for deep-sea mining. Additionally, temporal variability of these habitats also have a profound influence on ecosystem function and encompasses a broad range of scales, e.g., short-term mesoscale oceanographic elements associated with topographic features (upwelling on seamounts, downwelling/upwelling in canyons) or atmospheric forcing (deep eddies and internal waves).

Climate change will likely alter habitat suitability, impacting resilience and connectivity of deep-sea species. The ocean floor hosts diverse habitats largely reflecting its complex hydrography and geomorphology (e.g., ridges, trenches, canyons, volcanic and seamount chains, abyssal plains, and sediment covered slopes). This habitat heterogeneity promotes species, genetic and functional diversity. Biogeographic and genetic diversity patterns reflect both the connectivity of actual populations (i.e., the capacity of larvae to disperse and settle in a network of suitable habitats) and their evolutionary and colonization history over seafloor habitat features. Changes in habitat suitability that influences species connectivity can be particularly important when considering Marine Protected Areas (MPAs) as these changes can impact MPA's ability to internally maintain populations. 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.

It is also particularly important to consider habitats where species already live at their edge of their tolerance thresholds. Changes in these ecosystems may occur faster than other areas. For example, cold-water corals in low oxygen or corrosive (below aragonite saturation level) waters, or living in warm conditions such as the Mediterranean deep-water (13-14°C) are very sensitive to small changes. Similarly, organisms in the polar deep-sea where cold temperatures have selected for specially adapted species.

Lastly, global-change stressors can affect deep ocean biodiversity and related food webs through changes in the quantity and quality of particulate organic carbon (POC) exported to the deep ocean. With the exception of chemosynthetic ecosystems, the deep pelagic and benthic realms are largely fueled by POC (and larger detritus) produced by phototrophs in the upper 100 m and exported to the deep ocean. Current research suggests that POC flux is highly sensitive to global change (e.g., Soltwedel et al. 2016) and is projected to decline throughout much of the ocean by 2100 (Sweetman et al. 2017). As such, there is a need to understand how changes in surface productivity (e.g. due to warming, nutrient change related to freshwater inputs or sea-ice loss, changes in upwelling and vertical mixing) are affecting deep-sea food webs, primary productivity, secondary productivity and functional groups in the water column and at the seafloor. For example, when combined with other environmental stressors, the decrease in POC could have compounding effects on deep-sea animals as their energy demand will increase with stress but less food will be available.

The composition and degree of degradation of organic material exported at depth is a key factor that affects its nutritional quality. Predicted changes in surface productivity may cause a shift in phytoplankton assemblages from fast-sinking diatoms to slow-sinking picoplankton, leading to water column POC degradation linked to oxygen consumption and CO_2 generation, and a decline in the quality of organic matter reaching the seafloor (Muller-Karger et al. 2018). As such, the deep-sea research community needs to understand the physical processes governing the transfer of particles to the deep layers, the microbial communities that respire and degrade this organic matter, and how deoxygenation, warming, and acidification influence, and are influenced by, microbially-mediated processes in order to fully understand the scope of these changes. POC flux has been identified as one of the key factors connecting climate change to faunal communities and their functions in a variety of deep seafloor ecosystems, particularly in abyssal habitats which are naturally severely food limited (e.g., Jones et al. 2014, Yool et al. 2017).

More generally, there is a need to monitor both long-term trends and the natural variability of biotic and abiotic key variables in order to anticipate how biodiversity and habitat changes might alter deep-sea ecosystem functions and the services they provide. To date, few deep-seafloor large observatories have been established that address time-series observations of communities and ecosystem function across size classes and those that do exist are restricted only to a few regions of the oceans. These include large-scale sustained national initiatives such as the Ocean Observatories Initiative (OOI) Regional Cabled Array (RCA) and Ocean Networks Canada (ONC) with a focus on the Northeast Pacific that span the seafloor and the entire water column (Kelley et al. 2014). Somewhat smaller, but nevertheless comprehensive, observation programs run by individual institutions can also be found in the North Atlantic and Fram Strait (Soltwedel et al. 2005, 2013, Lampitt, et al. 2010). Questions of interest for these observatories include (1) response of benthic macrofauna diversity, functional groups and biomass to the heterogeneity of organic sedimentation fluxes, (2) growth/mortality of habitat builders, and (3) interplay of burrowing species or symbiotic invertebrates with chemolithotrophic processes and their capacity to sustain nutrient cycling, fix carbon, and regulate the formation of toxic sulfide and other chemical compounds.

Opportunities for improved observation are offered by recent advances in low-energy and low-cost miniaturized sensors, batteries and robotics development to expand the network of autonomous monitored stations (as done for the water masses with Argo) through networks of seafloor observing platforms and use of benthic landers hosting fixed biological survey equipment (e.g. benthic chambers, sediment traps), 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.

E. POLICY DRIVERS AND INTERNATIONAL LEGAL CONTEXT

International commitments to end poverty, protect the planet, and ensure prosperity for all, as embodied in the UN's 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), are driving demands for science to inform decision making. SDG 14 ("Conserve and sustainably use the oceans, seas and marine resources for sustainable development")[8] specifically calls for an increase in scientific knowledge, research capacity, and marine technology transfer to improve ocean health and to enhance the contribution of marine biodiversity to economic development, particularly in developing nations. Ecosystem-based approaches to management, which require an understanding of environment-life interactions and interconnectivities between the deep ocean and shallower waters, are seen to play a key role in achieving these aims. Just as ocean research is biased toward shallower depths, so too is the science used to inform decision making. The deep ocean research community needs a focal voice to contribute to decision making discussion; DOOS can fill that need.

As recognized in SDG 14, the UN Convention on the Law of the Sea (UNCLOS) provides the overarching legal framework for activities affecting the conservation and sustainable use of the ocean and its resources. UNCLOS obligations include the duty to 1) protect and preserve the marine environment; 2) protect rare and fragile ecosystems and the habitat of depleted threatened or endangered species; 3) properly conserve and manage living marine resources; and 4) prevent, reduce, and control pollution, as well as monitor the risks or effects of

[8] https://sustainabledevelopment.un.org/sdg14

pollution on the marine environment. While UNCLOS adopts a regional approach that divides the ocean (and States' rights over resources) into areas within and beyond national jurisdiction, the deep ocean straddles and interconnects national and international jurisdictions. Implementing UNCLOS's many environmental and resource requirements will thus require an understanding of deep ocean health and monitoring of change. UNCLOS is complemented by a wide array of environmental and sector-specific related agreements and bodies that deep ocean observations can inform (Table 1).

Table 1. *Environmental and sector-specific related agreements/bodies informed by deep-ocean observations*

Name	Purpose
Convention on Biology Diversity	Avoid loss of biodiversity
UN Agreement on Highly Migratory & Straddling Fish Stocks	Sustain shared fisheries resources
Convention on Migratory Species	Safeguard highly migratory marine animals
International Seabed Authority (ISA)	Mining related activities on the international seafloor
Food and Agriculture Organization (FAO)	International fisheries policy
International Maritime Organization (IMO)	Merchant shipping and dumping of wastes
Regional Fisheries Management Organizations (RFMOs)	Directly responsible for managing fisheries
Regional Seas Organizations (RSOs)	Coordinate policies and activities related to conservation and sustainable development issues of shared concern, such as marine pollution and specially protected areas
Large Marine Ecosystem (LME)	Strategic Action Programs (SAPs) in 23 LMEs are starting to expand their traditional continental shelf focus to include influences from deeper offshore waters

Additionally, the UN Framework Convention on Climate Change (UNFCCC, Figure 4) and its related Paris Agreement have recognized the importance of ensuring the integrity of all ecosystems, including oceans, and the protection of biodiversity. In this regard, the effective implementation of the UNFCCC and Paris Agreement will require an improved understanding of the role of the deep ocean in climate change-related processes, its absorptive capacity as a carbon sink, and related impacts and changes over time.

Figure 4. *Plenary session of the UNFCC during COP 24 in Katowice, Poland.*

Two ongoing legal developments from 2018 are worth particular attention from the deep ocean research community. First, the ISA is developing regulations for deep seabed mining in the "Area" (i.e., seafloor in international waters, defined by UNCLOS). These regulations must be informed by the specific UNCLOS obligation (Article 145) to ensure effective protection of the marine environment from harmful effects that may arise from mining-related activities. Adequate baselines and effective monitoring of impacts through long-term observations, will be essential components of any related environmental management strategy.

Second, the UN is developing an international legally binding instrument for the conservation and sustainable use of marine biodiversity beyond national jurisdiction (BBNJ). This new instrument is envisaged as providing a global platform for area-based management tools including marine protected areas, supporting environmental impact and strategic environmental assessments, enhancing capacity development, accessing appropriate technologies, and sharing benefits derived from the use of marine genetic resources.

II. DOOS GOALS AND OBJECTIVES

A. DOOS PROJECT TERMS OF REFERENCE

The DOOS Terms of Reference were proposed during the 2016 DOOS Workshop and subsequently approved by the DOOS SC during their inaugural meeting in 2017.

Box 3. DOOS TERMS OF REFERENCE

Build understanding of what is most important to observe.
- Identify important science and societal questions and relevant variables for stakeholders
- Identify the high priority processes and phenomena in the deep ocean to observe

Provide a hub for integration opportunities:
- Act as an agent to coordinate existing deep observing activities across disciplines to form a systematic, sustained deep-ocean observing system.
- Act as an integrator to create linkages among appropriate research, intergovernmental, industry, regulatory and funding agencies to achieve deep-ocean societal objectives through science.
- Foster observing activities at community identified multi-use, multi-disciplinary sites, representing different key biogeochemical and ecological regimes and questions.

Coordinate observations to:
- Utilize existing platforms for new sensors or integration of physical, biogeochemical and biological sensors to improve observing efficiency.
- Document the state of deep-ocean observing
- Identify standards and best practices for observing the deep sea

Develop deep observing requirements
- Identify the EOVs specific to the deep ocean and add deep-ocean specifications to existing GOOS EOVs
- Identify gaps (knowledge, geographic, variables, technical, data) and emerging systems relative to the key science and societal questions

Build readiness in observing technology and techniques
- Promote new technology developments and assess their suitability to address key scientific questions, management issues, or early warning of ocean hazards/extreme events.
- Build ability to use technologies, and facilitate transfer of technology to developing countries

Foster availability, discoverability, and usability of deep-ocean data.
- Promote fit –for-purpose data

Create a common community science implementation guidance / plan for deep-ocean observing
- Advocate for deep observations particularly as outlined within the science implementation plan

B. STAKEHOLDERS OF DEEP OCEAN OBSERVATIONS

DOOS stakeholders include scientists, natural resource and technology industries, as well as regional, national and local governments, non-governmental organizations (NGOs), and intergovernmental organizations (IGOs) (Figure 5).

Scientists. Among research and monitoring stakeholders, improved deep ocean observation as an integral part of GOOS will benefit scientists engaged in deep-ocean observing programs (e.g., GO-SHIP, Argo, OceanSITES, OOI, ONC, DONET). The DOOS Project will facilitate planning for scientists that use deep-ocean data generated by others (for cruise planning, modeling, analysis, ground-truth analysis) by ensuring sustained data generation, availability, and interoperability.

Industry. Industries that may benefit from DOOS include 1) manufacturers of instruments used to make deep-ocean observations whose products could benefit from advocacy for their use, 2) generators of ocean data required for baseline or impact assessments (e.g., fishing, mining, oil and gas operations), and 3) users of ocean data required to plan or guide successful operations (e.g., shipping, submarine telecommunications cables, marine genetic resources).

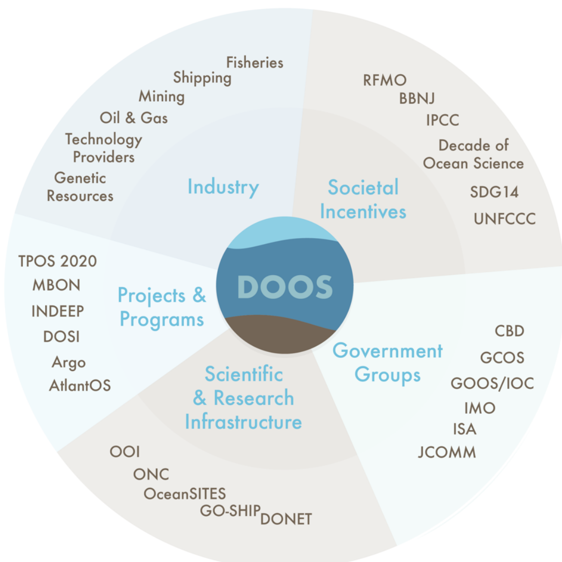

Figure 5. *The many-faceted nature of deep ocean stakeholders crossing a range of sectors and jurisdiction (as referenced in this report).*

Government. DOOS will work with governments, UN agencies, IGOs and NGOs to use deep-ocean information to inform and guide regulation and policy. Examples include those involved with the ISA, Regional Fisheries Management Organizations (RFMO), the International Maritime Organization (IMO), the Convention on Biodiversity (CBD) and the Intergovernmental Panel on Climate Change (IPCC). Government benefits from deep ocean data include early warning observations (e.g., of seismic, tsunami, hypoxic events) and weather and climate prediction. There are a growing number of entities engaged in ocean resource management, conservation and stewardship that use deep ocean data for strategic environmental analysis, planning, designation of protected areas, accident response and other forms of decision making.

Additional Stakeholders. DOOS capacity building efforts will benefit additional stakeholders in the realms of ocean literacy, education, general public outreach, STEM development, technology advancement, and technology transfer. It is anticipated that DOOS can assist or collaborate with parent or parallel scientific networks through joint initiatives and goals, such as ongoing efforts related to joint SDG 14 voluntary contributions and inputs to BBNJ as well as upcoming efforts with the Decade for Ocean Science and collaborations with TPOS 2020, AtlantOS, DOSI/INDEEP, MBON, and others. As the DOOS activities evolve, and new uses of the deep ocean by humans develop, it is likely that novel, possibly unexpected DOOS stakeholders and engagement endeavors will emerge.

C. RELATIONSHIP AND CONTRIBUTION TO GOOS AND OTHER INTERNATIONAL INITIATIVES

1. RELATIONSHIP TO GOOS

As a GOOS Project, a primary outcome of DOOS will be to seamlessly integrate the implementation of the deep ocean observing strategy as part of the GOOS legacy (Figure 6). The GOOS program operates under the auspices of the Intergovernmental Oceanographic Commission (IOC) of the UNESCO. It consists of a series of observing networks and regional alliances focused on sustained ocean observing programs guided by well-vetted ocean science and societal needs. Along with the WMO-IOC Joint Technical Commission for Oceanography and Marine

Meteorology (JCOMM), GOOS coordinates the integrated implementation of unified *in situ* and satellite observations.

The goal of GOOS is to promote and coordinate the development of a truly global, full-depth, sustained ocean observing system that adequately samples essential variables across physical, biogeochemical, and ecosystem components. Recognizing the daunting task that this represents, GOOS monitors several focused Projects designed to develop systems and strategies that fill urgent and emerging gaps in the observing system. DOOS is one of these projects along with Tropical Pacific Observing System (TPOS) 2020, Atlantic Observing System (AtlantOS), Global Ocean-Acidification Network (GO-AN), and the Animal Telemetry Network (ATN).

While DOOS is managed independently of GOOS, their activities and priorities are aligned through utilization of the Framework for Ocean Observing (FOO), developed following OceanObs'09 Conference in Venice, as a guiding set of central processes and principles – e.g. the concept of EOVs and the development of a fit-for-purpose observing system through the maturation of requirements, technologies, and information, all driven by scientific and societal need.

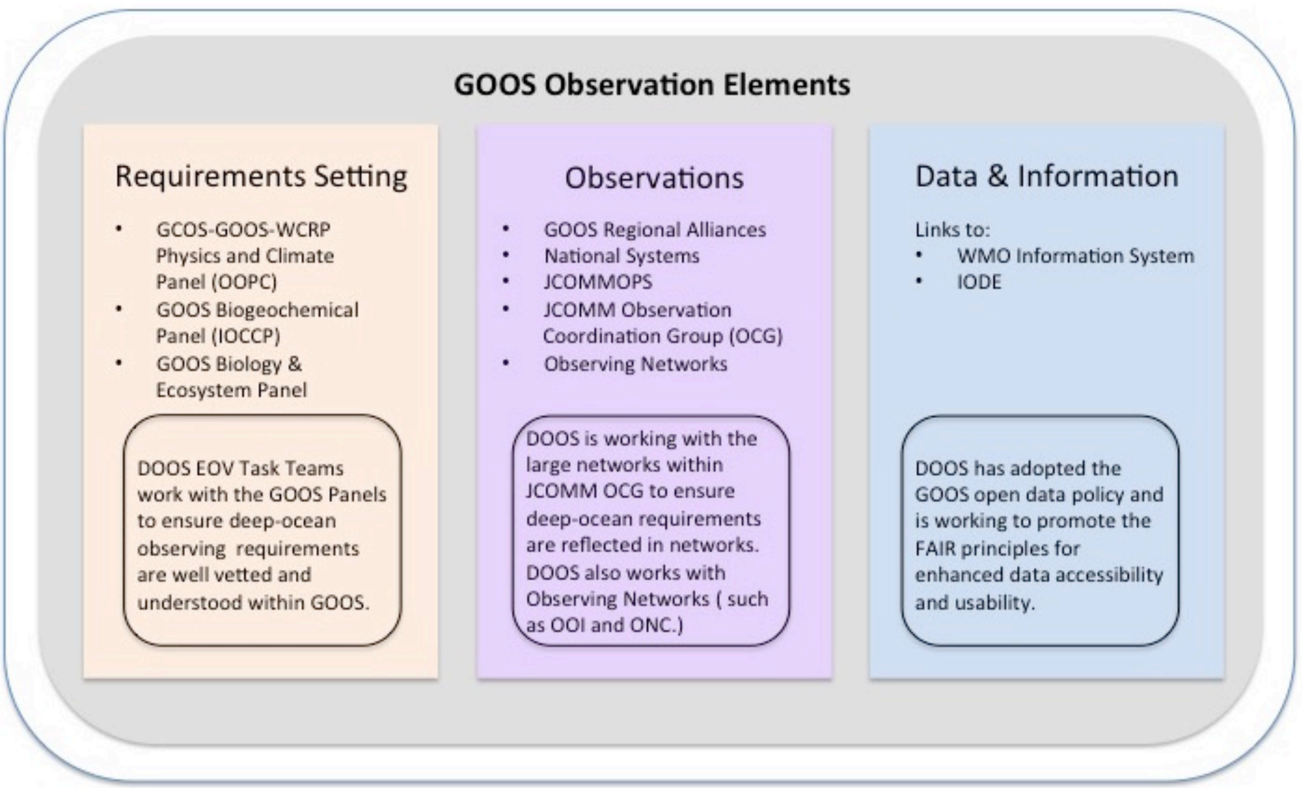

Figure 6. *The Deep Ocean Observing Strategy (DOOS) operates within the Global Ocean Observing System (GOOS) under the auspices of the Intergovernmental Oceanographic Commission to promote GOOS observation elements.*

DOOS interacts with the GOOS Steering Committee (GOOS SC) and the three disciplinary panels: the Physics and Climate Panel, executed by the Ocean Observations Panel for Climate – OOPC; the Biogeochemistry Panel, executed by the International Ocean Carbon Coordination Project – IOCCP; and the Biology and Ecosystem Panel. In particular, DOOS is working with the expert panels to evaluate the list of EOVs developed by GOOS (as well as related Essential Climate Variables[9] supported by the Global Climate Observing System or GCOS) to ensure that EOV specifications are revised to fully consider deep-ocean perspectives. Additionally, where variables of significance to the deep ocean are found to be missing or have inadequate sampling requirements, new deep EOVs are proposed and assessed via FOO processes. Lastly, DOOS is contributing to the overall GOOS effort by developing an interdisciplinary strategy to enable the concurrent sampling of EOVs across all three disciplines.

In addition to activities that articulate and mature deep ocean focused EOV measurement requirements, DOOS works through GOOS programs and networks to contribute to and demonstrate best practices and technology development. This effort involves the design and evaluation of observing systems and the oversight of demonstration projects and process studies. Demonstration projects and process studies provide a blueprint for global deep-ocean observation technology readiness, and a deep-ocean data policy that supports the FAIR principles of Findability (discovery), Accessibility, Interoperability, and Reusability. Demonstration projects are currently proposed for the Clarion Clipperton Fracture Zone, the Northeast Pacific, and the Azores Archipelago (see section VII).

2. RELATIONSHIP TO OTHER DEEP OBSERVATION ENDEAVORS

One of the main objectives of DOOS is to serve as a communication hub for the deep ocean stakeholder community. As such, an important element of DOOS is to engage with existing deep-ocean scientific networks, large deep-ocean observing programs, and seafloor observatories. DOOS currently has significant relationships with existing deep-sea scientific networks such as the Deep Ocean Stewardship Initiative (DOSI) and the International network for scientific investigation of deep-sea ecosystems (INDEEP), as well as other organizations. For example, DOOS contributes to the Marine Biodiversity Observation Network (MBON) and Blue Planet of the Group on Earth Observations (GEO) through the development of protocols and standards for collection of biodiversity observations in the deep ocean. Additionally, DOOS collaborates with the Ocean Best Practices (OBP) working group of the Intergovernmental Oceanographic Commission (IOC).

3. OVERALL BENEFIT TO DEEP-OCEAN OBSERVING

Wide participation in well-established international groups and organizations will facilitate the important work being done to collaborate across disparate observing systems to foster more wide-spread awareness and coordination. For example, making data products available across a broadening user base, including assimilation and modeling communities. It will also enable increased understanding and articulation of linkages among EOV observations supporting wider use and stronger justification for deep ocean data collection efforts.

[9] https://unfccc.int/sites/default/files/gcos_ip_10oct2016.pdf

III. ESSENTIAL OCEAN VARIABLES

The EOV concept adopted by DOOS is specifically based on the principles outlined in the FOO (Lindstrom et al. 2012) and aligned with the identification and specification processes utilized by GOOS. During the GOOS variable identification process, panels select variables that are 'fit for purpose' based on their ability to address pressing scientific questions and societal challenges as well as their readiness for operational observations, i.e. their impact and feasibility. DOOS is addressing EOV's both in terms of adding a deep ocean perspective to existing EOV's and adding additional deep ocean specific EOVs. EOV's are observed in different regions to address different observing requirements; the space and time sampling requirements and accuracies similarly vary in order to address these requirements. For deep observing, space and time sampling and accuracies required for EOV's will likely be different than for the upper ocean. Additionally, variables not considered essential in the upper ocean, may be of different impact and feasibility in the deep ocean.

The initial selection of EOVs in DOOS began with the development of the DOOS Consultative Report by a multidisciplinary writing team of experts in the field of ocean physics/climate, carbon/biogeochemistry, and biodiversity/ecosystems that went through a community review. At the December 2016 meeting, members of the DOOS community reviewed the EOVs suggested in the Consultative Draft in terms of how well they serve the big challenges of deep-sea science and society and to what extent observations considered essential for the deep ocean were covered by existing EOVs. This review confirmed the need for a deep-ocean component as part of the EOV process that supports GOOS in ensuring that deep ocean observing requirements are met by GOOS EOV specifications and by suggesting additional deep-ocean specific EOVs where needed.

DOOS Project Task Teams have now been formed to facilitate the review of existing GOOS EOV categories of physics, biogeochemistry, and biology and ecosystems. While the Task Teams are disciplinary by nature, to facilitate specific input by experts and to harmonize with the approach taken by GOOS, the consultation process is constructed to maintain the DOOS multidisciplinary perspective. Leaders of the different task teams serve as members in the other Task Teams to integrate and harmonize the EOV process across physics, biogeochemistry, and biology/ecosystems. This acknowledges the necessity for observations from all disciplines to address the most important processes taking place in the deep ocean. The approach agrees with the phenomena/process-centered approach to requirements that was the foundation of the Consultative Draft Report and guided discussions during the DOOS Community Workshop and it acknowledges the fact that multidisciplinary observations are needed to address all key science questions identified by DOOS.

In consultations with representatives of the respective GOOS expert panels, deep ocean experts review the existing GOOS EOV 'Specification Sheet's and feed into the GOOS EOV revision process, as well as consult on potential uptake of additional EOVs identified by DOOS. This review and comments on specifications includes, where sensible, reference to supporting variables, as well as derived variables. With a focus on the deep ocean, these include the rationale for observations, the phenomena to capture and their characteristic scales, required levels of precision and accuracy and spatiotemporal coverage of observations, as well as existing and required observing technologies and networks. The development of these specifications is based on the existing GOOS documents where possible and involves all relevant initiatives in the field of time-series observations of the deep ocean. A key component of the FOO is an iterative feedback loop that repeatedly reviews scientific and societal requirements, the availability and feasibility of observation systems and methods, and the suitability of data and products provided. A regular iterative revision process will be established based on initial DOOS progress.

The FOO Framework promotes that EOVs must be capable of being observed or derived on a global scale, and must be technically feasible using proven, scientifically understood methods. DOOS recognizes the differing levels of readiness in developing EOVs across the three disciplines. Consequently, DOOS will identify ways to bring relevant deep-ocean variables, technologies, and data products that are in “concept” phase to a “mature” stage. As many of the biodiversity and ecosystem EOVs developed for shallow water are not relevant for deep water, the status, maturity level, and ubiquity of EOV coverage may also differ in shallow and deep water, depending on sensor depth ratings and accessibility.

It should be noted that DOOS, in keeping with GOOS, does not specifically call out a class of EOVs related to the solid earth. However, the seabed and underlying crust are, by definition, a boundary condition for deep ocean processes, and although many geophysical and geodynamical processes operate on longer timescales than is typically considered for ocean observation, understanding the state of geological systems is critical. In addition, strong coupling between the seabed and overlying ocean results in the potential for solid earth processes that do occur on observational timescales (e.g., volcanic eruptions) to drive large changes in physical, biogeochemical, and ecological processes. At present, solid earth related EOVs are included in each of the EOV classes described below as motivated by the science challenges (section I.D.). The potential exists to further refine these EOVs into a distinct solid-earth class.

A. PHYSICS EOVs

To address deep ocean physical challenges (section I.D.1.), a Physics EOV Task Team has been established consisting of external experts as well as appropriate DOOS SC representatives. The Task Team is (at the time of this writing) reviewing existing EOVs and preparing material for new EOVs by reviewing deep-ocean requirements, specific technological capabilities and maturity, and existing GOOS EOV specifications (Table 2).

Table 2. *List of GOOS Physical EOVs and DOOS EOVs under consideration (OBP has been approved as an emerging).*

Physics	
GOOS EOVs	• Sea state • Ocean surface stress • Sea ice • Sea surface height • Sea surface temperature • Subsurface temperature • Surface currents • Subsurface currents • Sea surface salinity • Subsurface salinity • Ocean surface heat flux • Ocean Bottom Pressure (emerging)
DOOS EOVs Under Consideration	• Seafloor Fluxes • Ocean Turbulence

Existing EOVs emphasize the upper ocean as that is where most measurements to date have focused. Of these EOVs, four can be applied to the deep ocean: subsurface temperature, salinity, and currents, and sea surface height. Sea surface height is an integrating (whole water column) measurement that is intimately connected with ocean bottom pressure (OBP,) and deep temperature and salinity (density) measurements. Subsurface temperature, salinity, and currents are critical elements to describe the deep ocean. Modifications to the present EOV specifications to take into account unique needs and elements in the deep sea will be formulated by the Task Team and forwarded to the Ocean Observations Panel for Climate (OOPC) for consideration.

Observations of these EOVs in the deep ocean can be provided by OceanSITES assets (moorings and other platforms used for long-term observations at established sites), OOI, Deep Argo floats, and in the future by SMART cable systems.

New deep EOVs suggested by the DOOS Physics Task Team include: ocean bottom pressure (OBP), ocean turbulence, and ocean bottom boundary fluxes (primarily geothermal fluxes). All three are required to fully address the equations of motion and their associated boundary conditions. The OOPC has already been made aware of the suggestion to include these in the set of GOOS physics EOVs. Additionally, ocean sound has been suggested as a deep EOV by the DOOS Biology and Ecology Task Team. As ocean sound has relevance for physics, it is also discussed in this section.

1. OCEAN BOTTOM PRESSURE

In a recent publication by Hughes et al. (2018), it was suggested that because OBP measurements allow for the examination of ocean circulation at global scales that “such measurements should be considered an important future component of the Global Ocean Observing System”. To date OBP has been approved as an emerging EOV by the GOOS OOPC. A distinct advantage of OBP sensors is their ability to resolve large-scale circulation variability on time scales of days, weeks and months, especially at latitudes poleward of ~40^{o} where surface and deep flows are most tightly linked.

Additionally, absolute OBP observations significantly contribute to understanding the causes of sea level (SL) rise by facilitating the separation of mass and steric/heat content effects (Ponte 2012). Whereas satellite altimetry SL observations measure overall changes in ocean height, OBP observations measure changes in ocean mass. Thermal expansion does not change the mass of the water column, and as such is not observed by OBP, whereas it does appear as a component of the ocean height increase observed in the satellite data. In contrast, glacier and ice cap melting does increase the mass of the oceans and is observed in OBP. By subtracting SL changes as observed by satellite from OBP, a measure of sea level rise from thermal expansion can be calculated.

OBP also complements the goals of the Gravity Recovery and Climate Experiment (GRACE) satellite missions. The GRACE mission and OBP observations share the objective of defining the geographical structure of mass changes in the oceans. However, GRACE data are limited to areas away from continental boundaries, are of a coarse horizontal resolution (at least a few hundred kilometers), and have time-space scale aliasing issues due to its non-repeating orbit. As such, distributed OBP sensors can complement these datasets by providing observations closer to the coast and with high resolution in space and time, though coverage is over a more limited area.

Though overall coverage is not as broad as satellites, well-placed OBP sensors can provide data that can inform basin-scale phenomena. For example, due to the dominant balance of forces between the horizontal gradients of pressure and the velocity structure of currents at periods longer than a day, accurate OBP observations can provide estimates of both basin-wide transports between OBP sensors located on opposing continental slopes and local bottom current amplitudes related to local energetic circulation features when deployed in proximity. All of these observations are needed to improve the accuracy of numerical models of the global ocean circulation.

At higher frequencies, OBP is sensitive to barotropic tides, internal waves and tides, infragravity waves, storm surges and tsunamis. The determination of the most accurate tidal constants possible, including secular changes, is essential to de-aliasing and correcting many other measurements, especially from satellites. In addition, OBP infrastructure would be well positioned to record seabed motion during seismic events. The potential for seabed seismic events to generate tsunamis, accompany submarine eruptions, and precede catastrophic ground-shaking on land make these observations critical to coastal security.

Measuring absolute OBP *in situ* remains challenging due to sensor drift and the need to accurately determine the sensor location in a well-defined earth coordinate reference system. These challenges have hampered the use of OBPs for studying interannual and longer time scale variability. Instead, OBP observations are limited to examining the variation between current measurements to provide a relative measurement of how water mass varies geographically.

OBP observations, however, have become more valuable in the last decade as modern technology developments (self-calibrating sensors, < 1 mm/y) are beginning to address the problem of long-term drift. For example, recent progress in satellite gravimetry (e.g. GRACE mission) and *in situ* sensor improvements have managed to minimize drift. This improvement is transformative and, when coupled with the (now in concept phase) SMART cable platform, greatly increases “feasibility” and “impact” in the FOO EOV context. The OOPC has approved OBP as an emerging EOV and have recommended that DOOS undertake the process of developing an EOV specification sheet, considering regional pilot studies, and planning for development and support of the global array.

2. OCEAN TURBULENCE

Larger-scale measurements of velocity, temperature and pressure allow for the assessment of water movement related to advection, i.e. “stirring.” It is much more difficult, however, to assess thermodynamic changes in water masses, i.e., "mixing", as it is ultimately molecular diffusion and can only be directly measured at these length scales. It is usual, but arguable (e.g. Ijichi and Hibiya, 2018), to assume that a portion of turbulent kinetic energy dissipation is consumed in mixing. Turbulent kinetic energy dissipation occurs at the Kolmogorov scale in velocity, which is cm to mm in the ocean.

Better constraining mixing is important in order to understand several ocean processes. For example, Munk (1966) showed that the meridional overturning circulation (MOC) is governed by a balance between the sinking of dense waters at high latitude and the diffusive mixing of density at lower latitudes. More recent work has shown that general circulation, temperature, and sea level (among other societally relevant variables) are sensitive to the distribution of turbulent mixing and vertical velocity across space and time (MacKinnon et al. 2017, Melet et al. 2013, Jochum et al. 2013, Mashayek et al. 2017). Many other biogeochemical processes also require a knowledge of mixing, including the efficiency of the carbon and biological pumps.

Observations of shear, strain, and overturning on 1-100 m vertical scales are presently used to infer turbulent mixing. Unfortunately, the associated parameterizations and assumptions for these variables are most suspect in regions of high turbulence, just where they are most important. The only way to overcome this is with globally distributed, geographically diverse, directly measured dissipation-scale (mm to cm) observations. The knowledge gained from detailed, long-term observations at a finite number of key sites coupled with routine broad-scale surveying can significantly improve the accuracy of turbulence parameters utilized in long-term climate prediction (e.g. MacKinnon et al. 2017).

Turbulence measurements at the "microstructure" scale (mm to cm) are now enabled for velocity for turbulent kinetic energy dissipation and temperature for the large-scale part of thermal diffusion spectra. Such measurements have been demonstrated using relatively new sensors that have also reduced the cost, communication and power requirements for sustained autonomous measurements and telemetered data (Becherer and Moum 2017). The connection between relatively routine equatorial turbulence measurements and O(1) impacts on El Niño and the annual cycles of tropical SST has been clearly demonstrated (Moum et al. 2013). Turbulence sensors can be placed on CTDs (e.g., GO-SHIP), moorings (e.g. PIRATA mooring array), gliders, and Argo floats; the latter is being proposed.

In initial discussions, the OOPC considered ocean turbulence important and useful in process studies, but requirements and methods for sustained observations were not yet clear or well developed. Spatial patterns of the order of magnitude of ocean mixing are currently estimated using parameterizations from temperature, salinity and pressure. The feasibility and cost effectiveness of direct ocean turbulence observations on a global basis has not been established. The panel agreed that further work is needed via process studies to develop a clear rationale for sustained observations, including potential multidisciplinary drivers. OOPC concluded that ocean turbulence was not ready for consideration as an EOV. Further work is needed to justify the case for global sustained observations and readiness of approaches; the DOOS Physics Task Team will continue to pursue this.

3. SEAFLOOR BOTTOM FLUXES

Compared to other deep ocean Physics EOVs, the flux of mass (water and salt) and heat between the ocean bottom and the ocean water is the least mature. The hydrothermal flux of water is small (0.005 Sv estimated) relative to all other boundary fluxes but the flux of heat is significant. The global average heat flux from the Earth's interior to the oceans is estimated to be ~100 mW/m^2 (Davies and Davies 2010, Davies 2013), as compared to the global net radiative imbalance of ~500 mW/m^2 (Loeb et al. 2012, Stephens et al. 2012, Johnson et al. 2016). Additionally important to note, is that much of heat flux across the seafloor is concentrated at mid-ocean spreading areas, whereas the abyssal, sediment-insulated bottom has much smaller values.

As we start to obtain data records longer than decades, accounting for bottom geothermal flux will be necessary, including the spatial variability, and likely also the temporal variability (e.g. underwater volcanoes). Note that heat fluxes can destabilize the density profile at depth, facilitating mixing. These geothermal fluxes are not accounted for in today's ocean circulation or climate models, but modeling groups are beginning to assess more rigorously the impact of geothermal fluxes on the large-scale ocean circulation (e.g., Emile-Geay and Madec 2009, Piecuch et al. 2015). Clearly, a major step forward would be the mapping of the seabed, subductions zones, and mid-ocean ridges as well as monitoring, for example, via seismo-acoustic remote sensing.

The OOPC in initial discussion found seafloor fluxes to be an intriguing proposition. The panel was interested in measurement approaches, whether the heat contribution was significantly changing, and the justification for sustained long-term monitoring. At this time, the OOPC conclusion is that bottom fluxes are not ready for consideration as an EOV. The panel considered this to be excellent proposition for a focused research proposal to form the basis of developing the concept of bottom fluxes as an EOV. Further, the inclusion of chemical constituents other than salt (e.g., methane, reduced metals) will be considered, possibly making this a cross-disciplinary EOV. The GOOS Task Team is taking this under consideration.

4. OCEAN SOUND

Ocean Sound has recently been adopted as a mature, cross-disciplinary EOV. While its “home” is in Biology and Ecosystems, there is a strong cross over with physics in terms of seismo-acoustics. Seismo-acoustics are used to remotely characterize seafloor processes including earthquakes and volcanic eruptions. These events can produce impacts that extend across the coastline and mark potential perturbations to other established and proposed EOVs, including geothermal flux and ocean circulation. In the water column, seismo-acoustics are sensitive to acoustic scattering by thermohaline and internal waves processes. Connecting these sensors in real-time with land networks could provide rapid warning times for earthquakes and tsunamis. Earthquakes and tsunamis at the ocean's margins have killed more than a quarter-million people since 2004, and large coastal populations are ever threatened. These phenomena are unstoppable, and hence, advanced warning is crucial. Further, the use of ocean sound in undersea positioning, communication, ocean acoustic tomography, and many other applications is ubiquitous as described elsewhere in this paper.

B. BIOGEOCHEMISTRY EOVs

The DOOS Biogeochemical (BGC) EOV Task Team has been formed from a team of experts of deep-ocean biogeochemical observations in order to add the deep ocean perspective to existing GOOS EOV specifications and define additional deep ocean EOVs where essential variables are missing (Table 3).

The starting point of this expert consultation was the DOOS Consultative Report that laid out deep-ocean specific EOV requirements and observation technologies, and community revision of the suggested deep-ocean EOVs during the DOOS Community Workshop in December 2016. Some representatives of the GOOS expert panels and experts involved in the GOOS EOV revision process are included in the group of DOOS experts to ensure the flow of information between DOOS and GOOS. Voluntary contributions to the DOOS BGC revision process are taking place at two levels of engagement, ‘guiding experts’ are 1) adopting specific EOVs to guide the specification and revision process, or 2) joining the task team to offer input to be provided to GOOS.

Guiding experts propose specific questions for the EOVs they adopt to facilitate targeted input by ‘consulting experts’. These questions focus on aspects where GOOS specifications are missing the deep ocean perspective, e.g. regarding relevant phenomena and their spatiotemporal scales, magnitude and range of signals to be measured, and existing and future observation platforms and networks. For variables missing in GOOS, guiding experts first develop DOOS EOV specification sheets following the structure of the current GOOS BGC EOV template. An initial review of GOOS BGC EOV specification sheets by consulting experts has begun, and new DOOS BGC variable specifications are being drafted. The results of this review will be summarized and guide experts who will then advise the Task Team accordingly.

Table 3. *List of GOOS Biogeochemical EOVs and DOOS EOVs under consideration.*

Biogeochemistry	
GOOS EOVs	• Oxygen • Nutrients • Inorganic carbon • Transient tracers • Particulate matter • Nitrous oxide • Stable carbon isotopes • Dissolved organic carbon • Ocean colour
DOOS EOVs Under Consideration	• Seafloor labile organic matter • Seafloor respiration • Seafloor fluid and gas effluxes (focus on methane) • Litter including microplastics

Several examples of phenomena of societal and scientific relevance that involve deep-sea processes, and call for extension of deep-sea observations, are introduced in Section I.D, including the global carbon cycle, deep-water oxygenation, nutrient pools, and seafloor fluxes. Here the biological pump is used as an example of a key process with a particularly strong deep-ocean component to highlight existing EOVS that can be updated with a deep ocean perspective, new deep EOVs that can be added, and multidisciplinary observations (Figure 7).

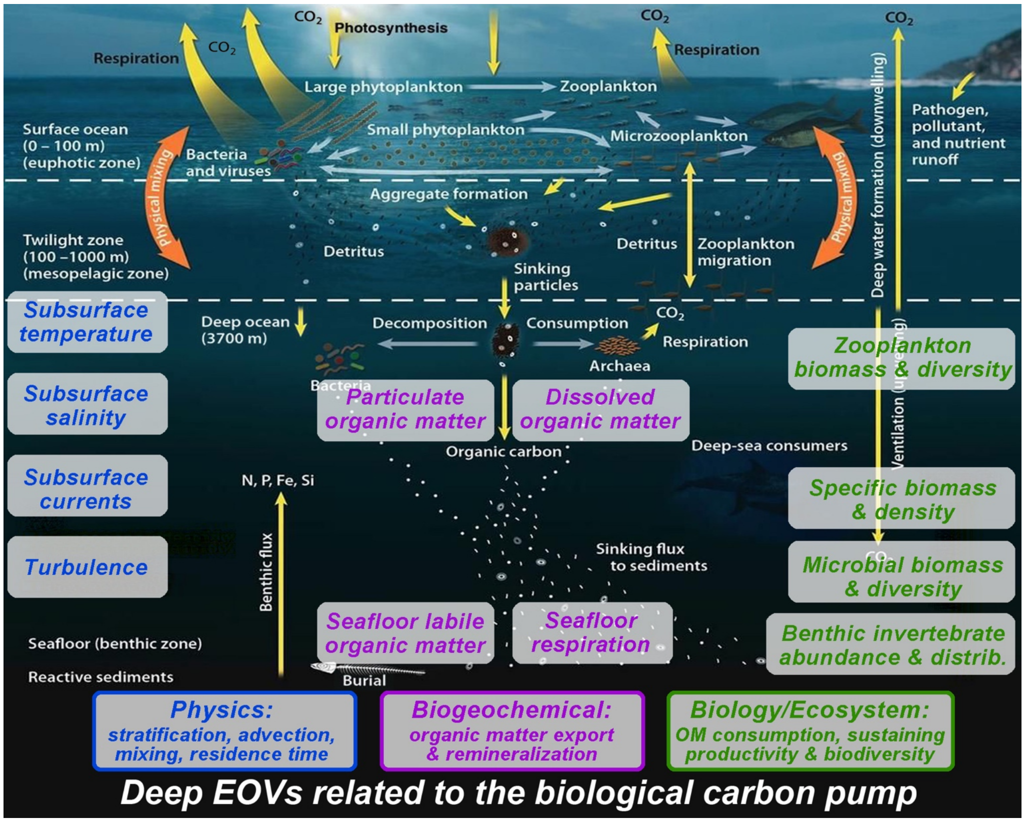

Figure 7. *Multidisciplinary observations throughout the water column are necessary to fully address the biological pump, and to provide information related to EOVs: From Levin et al. 2019 (doi: 10.3389/fmars.2019.00241). Background Image: U.S. DOE. 2008. Carbon Cycling and Biosequestration: Report from the March 2008 Workshop, DOE/SC-108, U.S. Department of Energy Office of Science[10].*

The biological pump transports organic matter produced in the surface layer to the ocean interior and the seafloor, thereby removing carbon dioxide from the atmosphere for potential long-term storage at depth. A large-scale quantitative assessment of the efficiency of the biological pump is thus of highest relevance for the global climate system. To properly address the associated processes, however, observations need to also include physical EOVs. For example, temperature and salinity measurements in the ocean interior are needed to address density gradients and their effects on particle sinking rates, as well as to connect to the carbon dioxide solubility pump (Figure 7).

Transient tracers EOVs are being examined by BGC experts in order to ensure the specifications include an accurate deep-ocean perspective. When accompanied by established as well as emerging physical EOVs (i.e.

[10] https://genomicscience.energy.gov/carboncycle/report/

subsurface currents and turbulence), these tracers contribute to assessing the origin of organic material, the fate of DIC released upon remineralization of exported organic matter, and its residence time in the deep ocean.

Other established biogeochemical EOVs (particulate matter, dissolved organic carbon, oxygen, nutrients, inorganic carbon) are also critical to review for the deep ocean perspective in order to address water column remineralization of organic matter, in terms of its role in the efficiency of the biological pump and consequences for biogeochemical conditions in the ocean interior. Additionally, in order to fully examine these processes established and emerging biology and ecosystem EOVs must also be examined. These include observations of meso- and bathypelagic zooplankton communities as well as observations of particle-associated microbial communities.

Finally, observations of seafloor labile organic matter availability and benthic community respiration, two additional deep-ocean BGC EOVs under consideration, would contribute to a comprehensive assessment of the biological carbon pump and its drivers that includes the dynamics in oxygen, nutrients and organic matter at the bottom of the ocean.

In addition, several other biogeochemical variables have been suggested by the deep-ocean community as potential deep EOVs and remain under consideration, including: seafloor fluid and gas fluxes (including greenhouse gases), litter and microplastics, redox-sensitive element distribution, and oxidation-reduction potential.

C. BIOLOGY AND ECOSYSTEM EOVS

DOOS has established a Biology and Ecosystems EOV Task Team comprised of experts from the main disciplines reflected in the EOVs also including some members from the GOOS Biology and Ecology Panel. The DOOS Biology and Ecosystems EOV Task Team is reviewing existing EOVS to identify those that could be applicable to the deep ocean given additional context and dimensions as well as identifying potential new deep ocean EOVs (Table 4).

Table 4. List of GOOS Biology and Ecosystem EOVs and DOOS EOVs under consideration.

Biology and Ecosystems	
GOOS EOVs	• Phytoplankton biomass and diversity • Zooplankton biomass and diversity • Fish abundance and distribution • Marine turtles, birds, mammal abundance and distribution • Hard coral cover and composition • Seagrass cover • Macroalgal canopy cover • Mangrove cover • Ocean sound • Microbe biomass and diversity (emerging) • Benthic invertebrate abundance and distribution (emerging)
DOOS EOVs Under Consideration	• Body size • Seafloor sponge habitat cover • Connectivity of species

Most of the EOVs suggested in the Consultative Report are already covered by the GOOS EOV Panels as either direct EOVs, variables that can be derived from existing EOVs, or as supporting variables identified in existing EOV specifications. For example, passive acoustics for the quantification of marine life, and biophony have been suggested as deep EOVs. However, the root variable that is typically derived from these acoustic data is some form of abundance, which is already captured in the existing EOVs.

Additionally, the newly described GOOS Ocean Sound EOV covers signals observed in the deep ocean that are important contributors to answering some of the key DOOS science questions (Figure 7). This may include biological acoustic signals from deep-diving marine mammals, soniferous fish, or sounds from invertebrates. It could also include human-generated sounds that either originate in the deep sea (e.g., mining) or reach the deep ocean (e.g., seismic exploration, shipping, sonar) and natural non-biological sounds such as earthquakes, rain or wind.

Several of the GOOS EOVs are not applicable to deep-ocean observing, e.g., mangrove, macroalgae, or seagrass cover, and phytoplankton biomass and diversity. Some, however, can be evolved to include context for deep-sea consideration, including hard coral cover and composition, zooplankton biomass and diversity, fish abundance and distribution, microbe biomass and diversity (emerging), and benthic invertebrate abundance and distribution (emerging). This will first occur through review of the existing EOV specifications and the identification of possible revisions. The GOOS Biology and Ecosystems EOV Panel will then be consulted as to whether suggested revisions might be accommodated.

For example, adding content related to deep-sea corals to the existing hard coral cover and composition EOV specification sheets has been identified as a priority by the Task Team. Deep corals are regularly the focus of special regulation including in the designation of marine protected areas and vulnerable marine ecosystem designation that influences fishery operation. Adding EOVs for other forms of living habitats will also be considered in the DOOS process, including sponge habitats.

Information on physical and geological characteristics of benthic habitats and their coverage (e.g., morphology, substratum type, granulometry) are needed to understand and predict benthic species distribution, their vulnerability to environmental changes, and the carrying capacity of benthic ecosystems. As many of these variables can be considered as temporally stable properties, they may only require a baseline survey. Time-series observations of these variables, however, may be required in specific areas of the deep ocean subject to strong natural or anthropogenic impacts, e.g., by trawling, fishing, deep-sea mineral extraction, volcanic activity, submarine landslides.

Body size has been identified as a key feature of ecological understanding that is fundamental to current theories such as the Metabolic Theory of Ecology (MTE) and the Dynamic Energetic Budget (DEB) Theory. The utility of body size information in forming budgets of the stocks and flows of carbon, as well as understanding several basic physiological dimensions, makes body size a valuable aspect to consider adding to many of the EOVs that refer to aggregating information about individual organisms, such as fish abundance and distribution.

Another DOOS EOV under discussion is the connectivity of species between locations. Connectivity, and the life history traits that enable connectivity (fecundity, pelagic larval duration, larval behavior, larval mortality, and larval dispersal), have been identified as key variables in understanding how areas impacted by seafloor mining might be able to recover after the burial or removal of large areas of seafloor life. The presence of a particular taxon at specific locations can be indicative of connectivity and is in effect an existing EOV. However, information on life-history traits and genetic variation adds considerable understanding of the degree to which different populations might be connected by various forms of dispersion.

D. MAPPING SCIENCE QUESTIONS TO EOVS, READINESS LEVELS, & NEW TECHNOLOGY NEEDS

One of the current goals of DOOS, as discussed in previous sections, is to assess relevant and emerging GOOS EOVs as they relate to the deep ocean, as well as to suggest additional new EOVs specific to the deep. Guiding that assessment are the six science questions articulated by DOOS in its initial framing as key drivers of deep-ocean observing (see Section IA.). Figure 8 reflects this examination, building a picture of how various EOVs can be used across multiple discipline areas to address DOOS science questions, as well as how EOVs can address many high priority questions. The content is based in part on knowledge collected by DOOS related to sensor and platform capabilities and from the Inventory for Deep Ocean Observing. Several factors were considered in the selection of EOVs for consideration by DOOS including technology readiness levels (TRL, NASA scale[11]) for sensors, platforms that carry those sensors, community capacity, requirements and best practice documentation, and the readiness of data and information systems to handle such data, including metadata standards. Notably, the figure remains a 'living document' for DOOS. DOOS will work with GOOS Panels, DOOS Task Teams and others to map these readiness and capability levels to identify gaps that may warrant attention.

[11] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

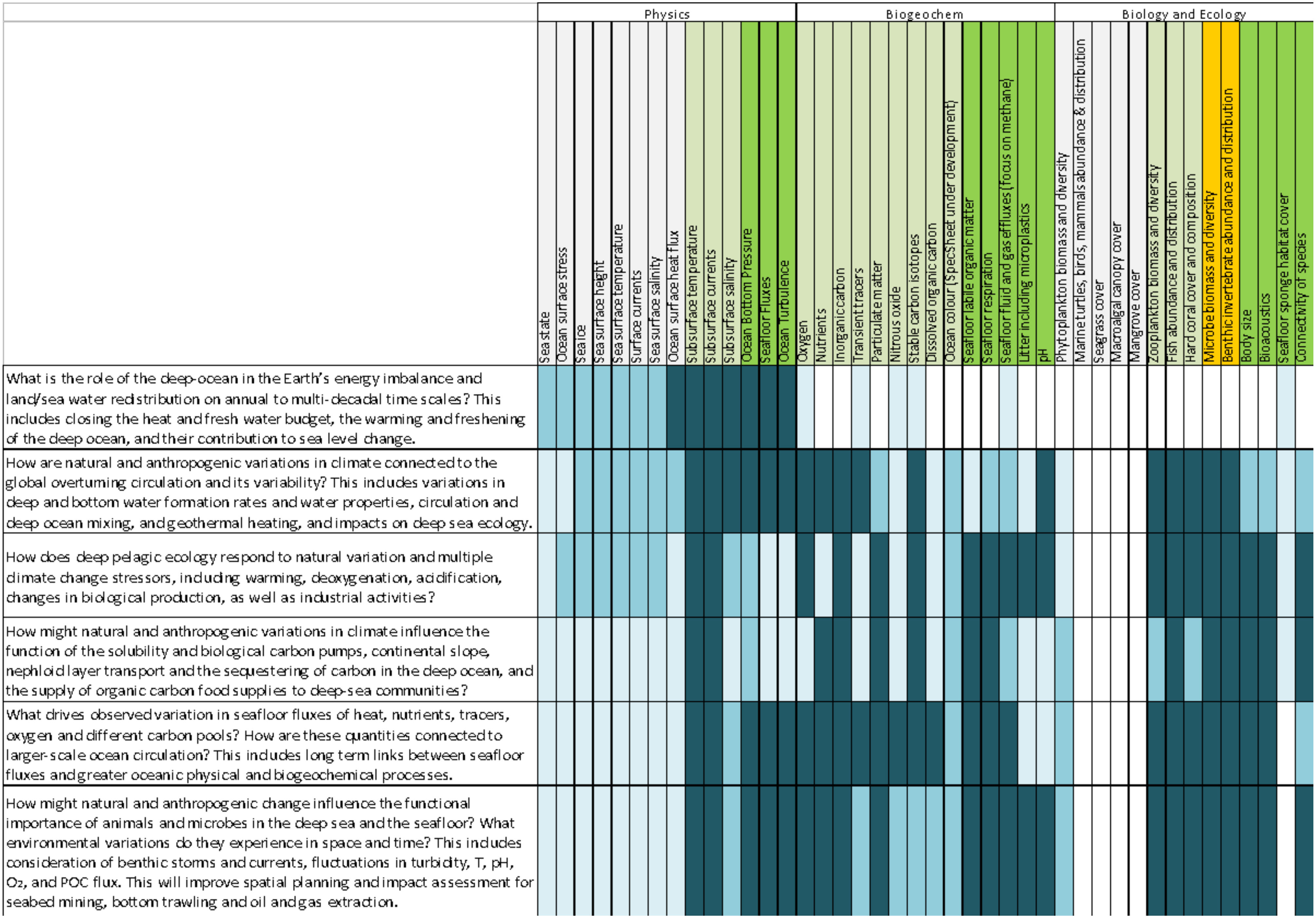

***Figure 8**: Qualitative representation of the EOVs needed to address the DOOS key science questions (see also part I). Saturation of colors in the matrix provide an estimate for the significance of the respective EOVs with darker shades indicating more relevance. The origin and context of the EOVs is indicated in the legend.*

IV. DEEP OCEAN OBSERVING PLATFORMS AND SENSORS

As an inclusive global network, GOOS seeks broad, observational coverage of the world ocean. DOOS seeks to facilitate deep-ocean observations across that coverage, which realistically will remain sparse. It is assumed that many of the deep sites added to the global system will arise from opportunities to accompany deployments of platforms for other networks, with a preference for those that will be sustained. The deep ocean observing community is challenged to expand the global observing system and determine the appropriate mix of existing sensors and platforms and the attendant deployment of new fixed and autonomous sensors and platforms.

For example, underwater exploration is presently supported by vessels operated by many skilled crew members, and underwater robots. As the exploration of deep-sea resources expands, and more countries have the technological capacity to access them, there are opportunities to expand our access to the deep ocean and support the development and validation of lower-cost mapping/observing technologies.

Toward this purpose, substantial efforts to develop the capacity to monitor deep-sea environments and biodiversity are required, including the sharing of skills and best practices for the use of existing instrumentation (e.g. robotics, sensors) and for the development of new equipment. All of this will require DOOS to bridge several disciplines each of which would benefit from DOOS engagement.

In addition to expanding the breadth of deep ocean observing, DOOS is interested in observation and sampling from more closely spaced regional or local arrays that may arise from process studies, research programs, or even deep-sea mining operations. These requirements are of interest as sources of information about the space/time variability and decorrelation scales of the deep ocean and will guide evolution of DOOS observing recommendations and activities.

A. PLATFORMS

A range of fixed and mobile platforms lend themselves to carrying sensors for deep observations. Ideal platforms are those that can be used in a globally distributed fashion, including research vessels, moorings, open-ocean and deep gliders, deep Argo floats, acoustically tracked floats, sensors on subsea cables, bottom landers and benthic ecological observatories (Figure 9). In more specific regions, cabled observatories, deep-diving mammals, and deep autonomous undersea vehicles (AUVs) can be utilized. Many of these platforms are mature and already exist within GOOS, though for some, the deep ocean versions specifically are in concept or pilot phases. Future work can expand on this development by combining the needs of the three disciplines (physical oceanography, biogeochemistry, and ecosystems) to make deep platforms more compatible and thus cost-effective for each discipline.

Figure 9. *Selected platform that carry sensors capable of deep-ocean relevant observations: moorings, satellites, research vessels, gliders, Autonomous Underwater Vehicles, smart cables, cabled observatories, Human Operated Vehicles, and marine mammals.*

Floats and Gliders: To improve global sampling coverage of the deep ocean, some combination of Deep Argo floats and deep gliders must be deployed. Both Deep Argo floats and deep gliders are extensions of existing technology. Deep Argo floats measure temperature-salinity-pressure through the full water column (up to 6000 dbar) every 10-15 days. Some Deep Argo floats are equipped with oxygen sensors. Biogeochemical and mixing parameters may be added in the future as well. Several nations are currently deploying Deep Argo regional pilot arrays to inform the design for a global Deep Argo array and to test the performance of the Deep Argo floats and their accompanying sensors (Johnson et al. 2015, Zilberman 2017). Repeat glider tracks are being established that are designed to increase the temporal and spatial resolution of shipboard surveys. The deployment of a combination of autonomous assets may provide ideal coverage, with deep gliders repeatedly measuring at a high resolution across strong and variable boundary currents, and Deep Argo floats distributed globally every 5°latitude × 5°longitude. In order to achieve full functionality of these mobile platforms, however, underwater “GPS” to improve mobile platform positioning and navigation must be adopted to provide accurate unaliased trajectories and water velocities (Duda et al. 2005).

Moorings: Sustained autonomous moorings, mooring arrays, and moorings connected directly to the Internet (i.e. OOI Regional Cabled Array) are currently sampling throughout the water column at a variety of key locations (e.g. OceanSITES, review by Glover et al. 2010). Autonomous mooring technology, however, must be improved to allow for more long-term and deep measurements. Additionally, sensor development is essential to permit operation at variable depths (i.e., robust vertical profiling), increase the lifetimes of mooring deployments (including energy supply), improve the stability and accuracy of sensor calibrations, decrease the cost of hardware and deployments, and allow continuous or occasional telemetry of data to shore. In the near-term, additional coverage of deep-ocean observations can quickly be made by adding BGC and ecosystem sensors to existing OceanSITES moorings at deep depths. Proven sensors can be incorporated in operational mode, while more advanced or innovative sensors can be added in pilot mode. Despite the benefits offered through the expanded use of existing moorings and arrays, cost and logistic considerations preclude a large-scale global deployment at sufficient spatial resolution required to quantify global heat and freshwater inventories, and changes in global circulation patterns.

Bottom Landers: Bottom landers are mobile facilities capable of hosting a suite of hydrographic, biogeochemical, optical, and acoustic sensors, as well as biological survey equipment. Landers are relatively immature platforms and are not often used in observatories. There are, however, a few examples of current use, such as the European Multidisciplinary Seafloor and water-column Observatory (EMSO) Generic Instrument Module (EGIM) that can either operate in mooring or bottom landing mode. This platform measures many of the existing and planned deep EOVs. Another example is the OOI Multi-Function Node (MFN). Though they presently act as anchors for moorings, the instrument frames could be deployed and are presently recovered independently, creating the potential for future expanded use. Autonomous surface vehicles (ASVs) can facilitate the use of bottom landers by serving as a communications gateway, and perhaps eventually assist in deployment and recovery. In the future, it may be cost effective to mass produce standardized bottom landers and work out efficient servicing procedures, but those are not capabilities currently available.

Ships: Reference measurements of deep-sea physical, biogeochemical, and biological variables are mostly taken during shipboard surveys. Due to the resource intensive nature of this type of observation, however, limited samples are collected. For example, the GO-SHIP program supports a limited number of trans-oceanic studies typically repeated at decadal intervals (Talley et al. 2016). Given this limitation, the temporal sampling is sparse with large gaps between ship-tracks, typically a few thousand kilometers. As this is such a high cost sampling collection method, in order to expand ship-based data, existing ship use must be optimized. For example, combining deep-sea sampling collection with maintenance cruises servicing other platforms, or collecting specific samples during unrelated research cruises.

Stations: At abyssal depths, time series studies of seafloor biological communities and processes have been conducted at specific stations in several of the world's ocean basins (Glover et al. 2010, Smith et al. 2013). For example, a few monthly visited stations have been instituted near mid-ocean islands (e.g., HOTS and BATS). Nearly all of the studies have witnessed changes across their time series in both hydrographic properties (e.g., > 20 mC fluctuations in abyssal temperature at the ALOHA Cabled Observatory, Howe 2014) and corresponding biological responses (Glover et al. 2010).

Cabled Underwater Observatories: Permanent, cabled underwater observatories provide access to power and communications bandwidth well beyond what is available to untethered moorings and seafloor platforms. The real-time, two-way communication and data flow enabled by the cable allows for event response capabilities (e.g. holding instrumented winched profilers in thin layers, adjustment of camera angles), as well as repeat, targeted sampling and analysis in both the water column and at the seafloor. Substantial innovations are to be expected through the use of cabled observatories, especially in the fields of biological oceanography and ecology, for example in monitoring biodiversity change and ecosystem function. Most of these cabled observatories have a suite of core instrumentation for measuring EOVs. However, they are geared largely to research and by their nature (and cost) have limited spatial extent. The maturation of long range and long endurance AUVs could help to extend the spatial footprint of fixed cabled systems in years to come.

Over the last two decades, various flavors of cabled undersea systems for ocean observing have been installed and are operating. Single node systems such as MARS (Monterey Bay at 900 m) and the ALOHA Cabled Observatory (ACO at 4728 m at Station ALOHA, the site of the Hawaii Ocean Time-series) can provide a fair amount of power and communications in a plug and play fashion. Regional scale systems, with multiple nodes spanning hundreds of kilometers, are operational today; examples include NEPTUNE Canada, the OOI Regional Cabled Array in the NE Pacific, and DONET off the coast of Japan. DONET also functions as a seismic/tsunami early warning system. The S-Net system off Japan is strictly an operational warning system (5000 km, 200 sensors), though its pressure sensors would be very useful for oceanographic research.

Environmental Sensing on Telecommunications Cables: Adding environmental sensors to trans-oceanic commercial telecommunications cable systems is a new effort in the concept phase (i.e., JTF SMART Cables[12]). These systems have repeaters every 50-100 km (e.g., mesoscale resolving along the cable path), which can provide modest power and communications. Current plans call for the deployment of ocean bottom pressure and temperature sensors with 3-D seismic acceleration at these repeaters to monitor ocean circulation, climate, tsunamis and earthquakes. There is approximately 1 Gm of installed cable in the ocean that is refreshed every 10-15 years for new technology. By adding sensors at repeaters each time a section of cable is refreshed, one could create several thousand seafloor mini-nodes spanning across ocean basins. It is likely that additional sensors such as salinity, passive acoustics, inverted echosounder/acoustic modems, bio-optics, among others could be added. This new application of riding “piggy-back” on existing, very mature, and highly reliable technology can provide a robust complement to current *in situ* and satellite sensing[13].

Deep Submergence Vehicles: Remotely operated and human occupied submersibles are required for local studies of deep-sea processes and high-resolution characterization of numerous EOVs. In addition, these vehicle systems are critical for maintaining *in situ* observation infrastructure. Autonomous underwater vehicles are a critical component of ocean observing with endurance and range that can exceed that of most human-operated vehicles. For the deep ocean, suitable AUVs are needed both for sampling (e.g., repeat surveys of ridge systems) and maintenance duties (e.g., energy and data transfer, calibrations). The development of resident AUVs that can provide a maintained seafloor presence through cabled docking stations would enhance their overall utility for deep-ocean observation. In order to make this technological leap, however, platforms (and sensors) need to move toward reducing mass, volume, power, and cost. In the next decade, it is expected that long range AUVs will be able to make observations of the full ocean depth while carrying a diverse sensor payload and making repeated observations; essentially acting as a ‘virtual mooring for months at a time on a single mission. Bottom rover vehicles that transit the seafloor are also increasing in technology readiness, with rover systems currently able to make measurements of seafloor respiration at daily scales over year-long missions. Positioning and navigation infrastructure would be required for both of these mobile platforms.

B. SENSOR STATUS AND DEVELOPMENT

The maturation of both sensors and platforms has progressed considerably in the last decade, including multiple commercial vendors for sensors measuring many EOVs as well as multiple manufacturers of AUVs, gliders,

[12] http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

[13] https://eos.org/meeting-reports/submarine-cable-systems-for-future-societal-needs

moorings, drifting floats and surface vehicles with innovative power and light sources. Many vendors also now market housing solutions suitable for deep-sea deployment as part of their regular product line. Together these provide a wide range of capability and capacity to deliver a step change in observing the deep ocean. There is a continuing need to develop sensors that can be supported on autonomous platforms and robotics, as the costs are orders of magnitude less than for ships (Figure 10).

In addition to the sensors described below by discipline, several elements not traditionally incorporated into ocean observing systems may be considered:

- Acoustics: Sonar; passive monitoring, ADCPs, fisheries echosounders, long-range positioning and navigation, acoustic tomography/thermometry, seismo-acoustics for earthquakes, submarine landslides and tsunamis, multibeam bathymetric echosounders, sub-bottom profilers
- Optical instrumentation: Video imagery, repeat large-scale AUV (image) surveys of the bottom for biology, holographic particle and plankton imaging, optical backscatter, Zooscan, stereo and light field cameras able to resolve objects in 3D;
- Time series via surface ship (e.g., coring, landers), ROV, HOV, hybrid vehicles (sampling and transects of various sorts - cores, hard substrates, biogenic substrates) and geochemical tracer applied to ecological studies;
- *In situ* samplers: Plankton recorders, Larval pumps, Sediment traps, fluid osmo-samplers;
- *In situ* Molecular/Genomic analysis, new autonomous chemical sensors O2, H2S, NO3-, CO2/pH, N20;
- Horizontal electric field to determine absolute barotropic velocity, using cables, “point” sensors on the bottom, and floats.

Figure 10. *Selected sensors that conduct deep-sea observations include: ADCP, pH, CO2, NO3, H2S, O2, N2O*

Physical and Climate Observations: Sensors that measure physical variables in the deep-ocean such as temperature, salinity, and velocity are relatively mature on platforms such as ships, moorings, and cabled observatories. They are currently being tested and matured for deployment on deep floats and gliders, as the miniaturization need to integrate into these mobile platforms requires power and sensor drift reduction.

On a smaller scale, the importance of obtaining better and ubiquitous sampling of mixing and turbulence has been recognized, resulting in new instruments that are near operational. While heat flux between the ocean and the seafloor forms a crucial boundary condition, more work needs to be done to make this measurement easier and more widespread. Satellite measurements of sea surface height are mature while gravity/bottom pressure is less so; both are essential for global coverage (they lack high temporal and spatial resolution). In general, the pros and cons of point versus integral satellite measurements requires assessment. As mentioned previously, OBP measurement is experiencing a transformative improvement with a new way of performing routine *in situ* calibration (better than 1 mm/y, Wilcock et al. 2018).

The implementation of long-range acoustic "GPS" should be considered in order to provide for long-term, high temporal resolution float tracking (velocity EOV, Duda et al. 2005), long-range AUV/glider navigation (including under ice), and tomography (temperature EOV). The same acoustic receivers can be used for wind and rain measurements, marine mammal and "soundscape" monitoring (ocean sound EOV); the same acoustic sources (low frequency, broadband) can be used for acoustic tomography. Acoustic GPS is technically mature, having been used in cabled (ATOC) and moored scenarios for decades, and is currently deployed in Fram Strait and the Beaufort Sea with an expansion into the Arctic planned. Benefits include: path averages that inherently suppress internal wave effects resulting in a high signal to noise ratio, a calibration-free design (a time measurement), quadratic growth in the amount of data with a number of instruments, nearly full water column sampling, and sampling at the speed of sound. Additionally, the use of the acoustic GPS enables high accuracy and temporal resolution of basin-scale heat content, complementing Argo and point measurements that are limited by aliased, sqrt(N) sampling (Dushaw 2018)

Carbon and Biogeochemistry Observations: Ship-based observations of inorganic carbon (alkalinity, pCO2, and pH) are in the mature phase, but are currently in the concept or pilot phase when deployed on other platforms. The analytical methods for inorganic carbon samples and certified reference materials for DIC and TA are well developed and used to meet long-term accuracy requirements (Dickson et al. 2007 and Wang et al. 2007). Improvements are in progress for refining the calibration of carbonate variables on autonomous platforms. These measurements will be useful to monitor short time variability and seasonality; however, they will likely not be accurate enough to monitor decadal changes.

Oxygen sensors are mature on ships and can be measured precisely with sensors mounted on a Conductivity, Temperature, Depth (CTD) package. The accuracy and long-term stability of oxygen sensors are close to being effective for autonomous vehicles, such as floats and gliders. A major advance has been the ability to reference oxygen sensors to air. For example, profiling floats are now being reconfigured to standardize themselves each time the sensor is at the surface (Bushinsky et al. 2016). The accuracy of inorganic nutrient measurements requires improvement in order to quantify changes in the deep ocean.

Optical tools, including chl-a fluorescence, optical backscatter, holography and light-field imaging, are in an emerging phase and can be used in profiling mode to determine particle type-and size-distributions in time or space (e.g. Briggs et al. 2011). From these observations, quantitative inferences can be made for metrics such as particulate organic Remineralization Length Scale (RLS) (Buesseler and Boyd 2009), or the types and sizes of particles associated with variation in RLS. Additionally, there are emerging sensors and methodologies for deep-ocean observations of particle and remineralization processes. Examples include next generation particle traps to improve reliability of vertical particle flux quantifications. These particle traps can be equipped with imaging systems to assess particle sizes and *in situ* settling velocities, can be or deployed with neutrally-buoyant drifting platforms.

Biodiversity and Ecosystem Observations: Biological oxygen demand (i.e. remineralization rate) observation techniques are in the pilot to mature phase across platforms. Oxygen consumption can be assessed by bottle or sediment core incubations, and *in situ* by chamber incubations or microprofiler measurements. Standing stock or biomass distribution across taxa and faunal size classes help to assess trophic structure of food webs. Some taxa and productivity can be assessed through the monitoring of bio-optical instrumentation, bioluminescence, or by sound collected via passive or active hydro-acoustic measurements. Stereoscopic imaging, holography and light-field cameras show promise for the quantification of fragile marine snow particles and important ecological quantities like gelatinous zooplankton. These measurements and spatial-temporal distributions require additional experimentation and understanding.

Several biodiversity and ecosystem EOVs are still in the concept phase for observing platforms. For example, ship-based sampling methods, while well established, are not suited for routine and frequent observations at large spatial scales. Lightframe On-sight Key Species Investigation (LOKI), flow cytometry, and various optical imaging systems provide opportunities to scale up capability towards broader collection of measurement of EOVs. However, while these imaging systems are mature, the automated species recognition technology to process the images is not. Work is needed to enhance value for biodiversity assessment. Trophic interactions can be observed through the study of stable carbon, nitrogen, sulfur isotope signatures, lipid biomarkers, and the accumulation of pollutants or tracers found in harvested or captured species. Physiological dispersion and adaptation to ecosystem change are commonly assessed through *in situ*, shipboard, or laboratory experiments. However, few deep-sea organisms are accessible for these analyses.

Diversity baseline and turnover studies are difficult due to the challenges associated with observation and sampling. There has been some progress in gene-based rapid biodiversity assessments such as metagenomics (eDNA) and DNA-barcoding, but successful application depends on baseline knowledge of species identity. Diversity indicators, such as rare versus abundant species, can be applied to estimate the relative abundances of organisms. Diversity indices can also be used to assess resilience to change, along with the restoration of communities in impacted environments. There is potential for proteomics, metabolomics and transcriptomics to contribute information about ecosystem function and services, particularly for microbial activity. However, the difficulty to validate biotic quality indexes will be as high as in the coastal zone. More research may reveal indicators species that can be used to reflect the status and health of different ecosystems and provide early warning of impending change.

Lastly, there are emerging observation technologies that can provide novel measurements, if they were to be matured. For example, continuously developing genomic methods could be applied to samples collected with automated samplers or even performed *in situ* to characterize microbial communities contributing to remineralization of settling organic matter. Other examples of emerging technologies are autonomous benthic crawler platforms for year-round observations of settling detritus and sediment community respiration to observe spatiotemporal variability in seafloor organic matter availability and remineralization.

C. CALIBRATION AND VALIDATION

Signals in the deep ocean tend to be orders of magnitude smaller than in the near-surface depths. This poses two challenges: 1) sensor precision needs to be sufficient to observe these smaller variations, and 2) data quality control needs to be sufficiently sophisticated to discover hard to identify outliers or otherwise problematic measurements. Because of these challenges, a thorough calibration and validation (cal/val) procedure that takes into account the low signal-to-noise ratios is needed. This is particularly true if sensors are deployed for extended periods of time (e.g. on moorings, gliders, floats) as opposed to brief ship-board surveys. Methods that have been successful include cross-comparing mooring sensors against ship-based CTD casts and water samples (e.g. Kanzow et al. 2006). Or, in the case of Argo, comparing values to the ever-growing reference database for salinity measurements. Ideally, such reference cal/val data is collected at multiple times during a long-term deployment and can then be used to not only provide an absolute reference at the beginning of the record, but remove long-term drift behavior from the sensor data. Much of the current technology used to observe EOVs in the deep ocean is less than mature, and for these, there will be a learning curve to establish absolute sensor accuracies, failure modes, and drift behaviors. A robust cal/val methodology is required to distinguish real signals from sensor artifacts. Further, the data management system processing these data must be able to handle quality control flags, multiple versions and updating of data records as new cal/val information becomes available, and proper metadata annotation to document what was done to the data and why.

V. DATA AND CYBERINFRASTRUCTURE

A. STATEMENT OF NEED

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. Progress in areas like climate change, where forensic challenges to scientific results are likely, require that data and supporting digital products be well documented, citable, and of known provenance. Furthermore, observations in the deep ocean are sufficiently 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.

B. DEFINITION OF SCOPE AND TERMINOLOGY

DOOS defines data as the suite of digital products that support and are derived from data, including raw data, derived data products, metadata, models, software, workflows, algorithms and other related code. For convenience, we use the terms “data” and “information products” throughout this implementation guide as a shorthand for the suite of artifacts covered.

C. STATUS OF DEEP-OCEAN CYBERINFRASTRUCTURE

Substantial and valuable global and deep ocean cyberinfrastructures exist, and it is not the goal of DOOS to reproduce existing resources. Instead, DOOS will work to identify and address opportunities for progress within and across the global and deep ocean observing community cyberinfrastructures.

Results from the Inventory of Deep Ocean Observing indicate that in many cases the data being collected by deep ocean observatories are being preserved and made freely accessible online to the larger community. There are also mechanisms being adopted, such as common data formats, metadata standards, controlled vocabularies for common concepts, and standard services, that are increasing the interoperability of existing data.

However, the experience of the DOOS Data Task Team members, suggest that areas for improvement remain. These include the discoverability of data by users not already familiar with an observing program; the ability to conduct one search in a central location as opposed to separate searches in individual repositories; wider adoption of interoperability mechanisms to facilitate the aggregation of data from many sources into larger synthesis or analysis; the systematic capture of the full provenance and processing history of data; and the appropriate description and sharing of information products beyond data (models, processing code, etc.). In addition, certain EOVs, generally the less mature ones, have more heterogeneous practices and less standardized and comprehensive data curation.

D. DOOS PRIORITY ACTIVITY AREAS FOR DATA AND CYBERINFRASTRUCTURE

As a GOOS project, DOOS supports the GOOS goals of fostering an open and interoperable system of regional, and global observing networks that rapidly and systematically acquire and disseminate data and data products to serve the needs of scientists, government agencies, educators, non-governmental organizations, and the public. Within this larger mission, DOOS has identified the following data-related activities as critical for the deep ocean community:

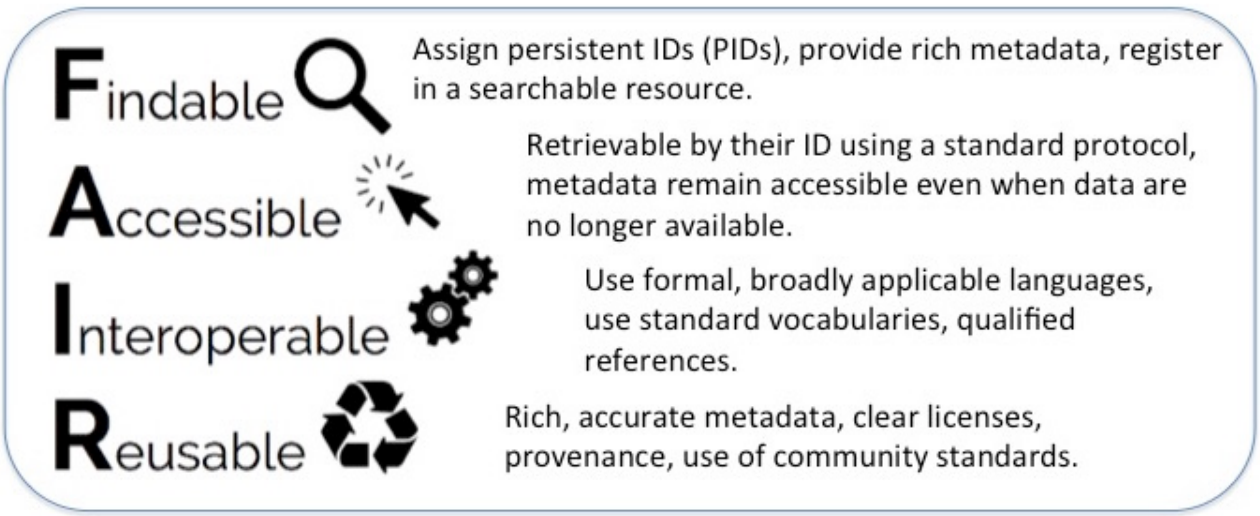

Figure 11. *FAIR guiding principles for current and historic deep-sea data.*

- Promoting and fostering practices described by the FAIR (findable, accessible, interoperable and reusable, Wilkinson et al. 2016) guiding principles for current and historic deep-sea data, particularly for data necessary to address DOOS priority processes and phenomena (Figure 11);
- Communicating GOOS data and information product recommendations and the FOO to the DOOS observatory operator community, and providing feedback to GOOS on any special considerations for deep ocean data;
- Identifying, evaluating, adopting, and recommending appropriate best practices and standards for data, metadata, and technologies, particularly where deep ocean data has unique or distinct requirements;
- Documenting the state of deep-ocean data preservation, identifying gaps, and assessing availability;
- Fostering capacity building and knowledge transfer for deep ocean data and information management globally, particularly where deep ocean data has unique or distinct requirements.
- Assisting scientists in identifying users of deep ocean data, including their requirements and priorities.
- Developing feedback mechanisms from data users to collectors and stewards of deep ocean data.

These activities will require education, outreach and liaison with several target communities:

- Oceanographers and other scientists using deep-ocean data and data products to raise awareness of the resources available and solicit input on unmet needs and requirements.
- Science task teams within DOOS and the DOOS leadership to support data-related activities.
- Deep ocean observing program operators and managers to inventory data and cyberinfrastructure resources and methods, understand challenges, promote best practices (including GOOS

recommendations), and convey scientist requests. For data and cyberinfrastructure managers, DOOS will additionally identify and seek to address opportunities for capacity building.

- Instrument developers to facilitate communication with scientists regarding any unique considerations for deep sea data and instrumentation.
- Projects and programs with existing deep ocean cyberinfrastructure to ensure that DOOS does not duplicate effort, but instead advocates for the specific interests and needs of the deep ocean community in larger forums.
- Industries working in, and collecting data in, the deep ocean and the ocean observing management and governance bodies to facilitate broader availability of industry data and transparency in operations.

VI. DEEP-OCEAN OBSERVATIONS INVENTORY

During the initial planning of DOOS, an online community-wide inventory tool was developed to assess the current state of deep-ocean observations. An inventory questionnaire was distributed to the deep-ocean community that solicited information concerning programmatic and academic research, standard operating procedures for data collection and sensor-specific variables, data archiving and dissemination, and expansion and collaboration opportunities. The inventory specifically sought to assess the status of deep-ocean observing with respect to water depths, platforms, sensors, variables measured, and temporal and geographic coverage. It was designed to inform the development of DOOS by identifying potential partners, as well as providing a common statement of requirements and an initial strategy for sustained global deep ocean observations. The inventory considers all EOVs, regions, technologies, and societal imperatives to extract high priority, feasibility, and GOOS fit-for-purpose actions for the next 5-10 years as well as identify gaps in geographic coverage, water depth, and EOVs in the deep ocean.

In preparation for the 2016 Community Workshop, an initial analysis of survey responses (through November 2016) was conducted. The overarching goal of the analysis was to identify gaps in geographic coverage, water depth, and EOVs. Overall, 79 responses from 52 organizations, representing 75 countries, and funded by 55 agencies were examined. Most program-wide sampling occurred across large depth ranges (200-6000 m) (Figure 12) and spatial scales (>1,000 km). The most common platforms used for observations were research ship surveys, bottle samplers, and moorings; the most common instruments were CTD's, oxygen sensors, and acoustic Doppler current profilers (ADCPs). The most common mature EOVs sampled were temperature, salinity, dissolved oxygen, and the carbonate system. Additional variables commonly suggested by respondents as key to include in DOOS were primary productivity, water velocity, inorganic nutrients, and species abundance and diversity. Many of these already exist as EOVs in some form.

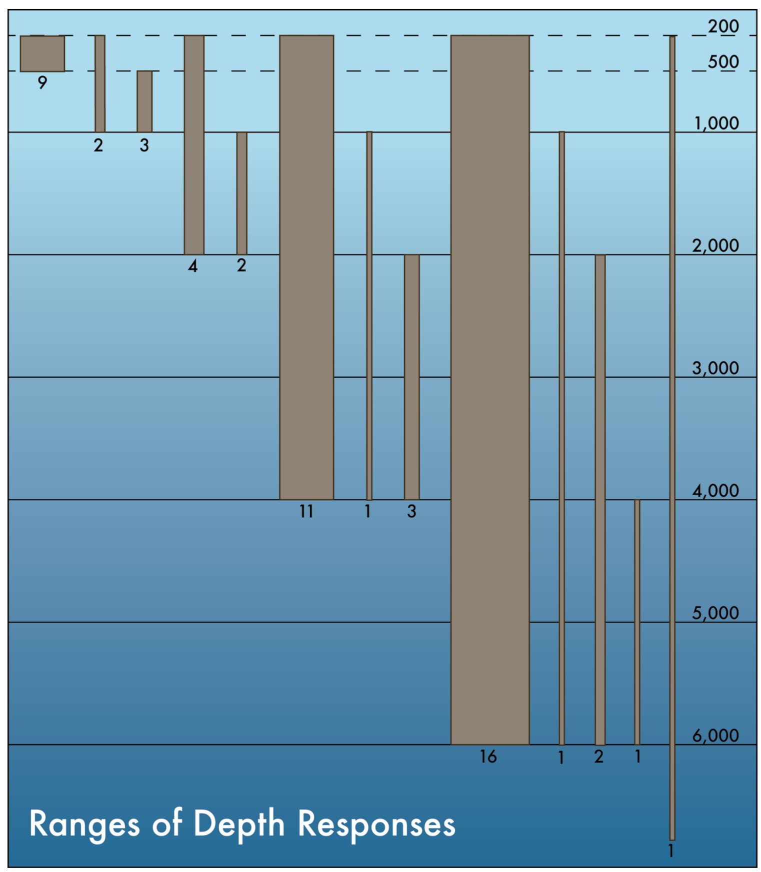

Figure 12. *Ranges of Depth Survey responses. Thickness based on the number of responses; number listed below each bar.*

Based on inventory results, an interactive map was created to provide a snapshot of observation efforts conducted across the globe and at different depths (Figure 13). Visualization of the data was produced via ESRI and can be found on the DOOS website[14]. The interactive map shows spatial gaps in observations and opportunities for expansion. The data obtained through the inventory feeds into the overall DOOS mission to bring together the broad range of expertise required to identify the challenges and seek solutions that will advance our understanding of and maintain the functioning and services of the deep ocean. The map is updated quarterly as data are modified and new inventory responses are submitted; updates to the inventory and gap analyses are on-going objectives of DOOS.

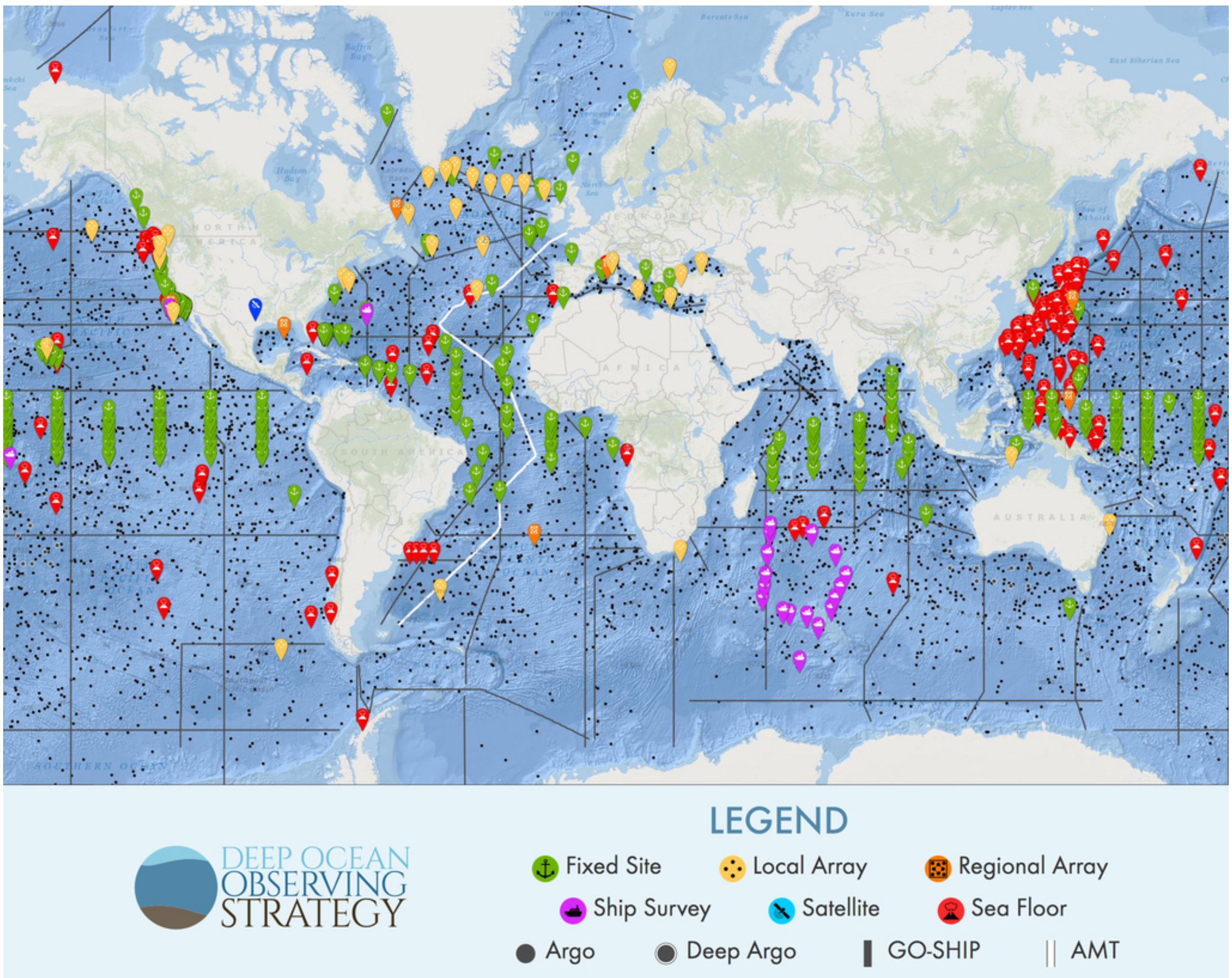

Figure 13. *Deep ocean observation efforts conducted across the globe. Data reflect information obtained through a DOOS inventory. See DOOS website[15] for an interactive version of the map.*

[14] http://www.deepoceanobserving.org/observations/deep-ocean-observations/

[15] http://www.deepoceanobserving.org/observations/deep-ocean-observations/

VII. DOOS DEMONSTRATION PROJECTS

A. CONCEPT AND PHILOSOPHY

DOOS seeks and supports projects that demonstrate the feasibility of sustained deep ocean observing, technologies to be employed in deep-ocean observing, and/or the impact and utilization of deep ocean observations for industry, policy, and management. Such projects may make use of existing infrastructure or may be based on new platforms. It is imperative that projects illuminate the end-to-end process of deep-ocean observing, processing and quality control of the data, and making the data readily available to users with appropriate documentation. All efforts will take into consideration the need for the advancement of well-vetted EOVs, state-of-the-art technological capacities for observation in the deep-ocean, and evolutive and modular dimensions of associated platforms, projects, and data products. Additional emphasis is on systems or approaches that hold promise to be extensible (scalable) from local to (quasi-) global coverage.

The following sections are overviews of three Demonstration Projects under consideration in 2019.

B. CLARION-CLIPPERTON ZONE

The Clarion-Clipperton Zone (CCZ), an abyssal plain in the eastern tropical North Pacific (Figure 14 A, B), provides a prime location for conducting a DOOS observational demonstration study. The CCZ is located on a fracture zone with polymetallic nodule mining potential in the central eastern Pacific (Lodge et al. 2014) and covers six million km^2 at water depths between 3800 and 6000 m. All seventeen deep-sea mining contractors with exploration claims in the CCZ must collect and provide physical, chemical and biological data to the ISA. Although oceanographic moorings have been deployed there for up to 3-years (Aleynik et al. 2017), the CCZ lacks any long-term observatory infrastructure. Many discoveries followed the recently expanded presence in the CCZ area, from regional faunal patterns (e.g. Vanreusel et al. 2016, Amon et al. 2016), discovery of new species (Lim et al. 2017, Gooday et al. 2017), and remarkable microbial biodiversity (Lindh et al. 2017), to a better understanding of temporal variation in seabed currents (e.g., Aleynik et al. 2017).

A demonstration project, if well integrated to ongoing studies by contractors, JPI Oceans and others, could feed data into the current Environmental Management Plan (EMP) for the CCZ (ISA, 2012), inform all stakeholders of the environmental setting and contribute to assessing the consequences of nodule mining. Sustained observations of a range of EOVs (from the sea surface to the abyssal seafloor) at or near CCZ locations will help address key scientific questions relevant to TPOS, DOOS carbon-cycle studies, deep pelagic ecosystem responses to deoxygenation, acidification and human activities, and provide a baseline for the understanding of the impacts of deep-sea mining.

DOOS carbon cycle goals that can be addressed in the CCZ include: evaluating carbon inventories in the deep ocean, constraining natural variations and trends in the biological pump and related carbon remineralization and sequestration processes, and improving high-frequency EOV observations at fixed-point reference stations.

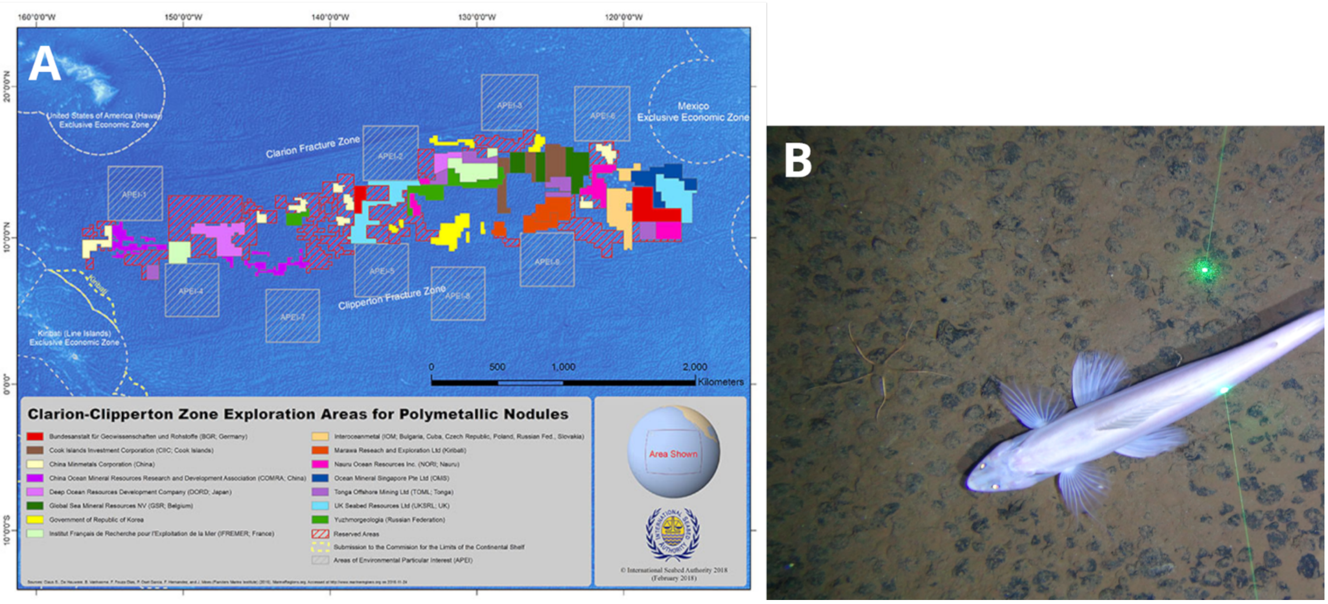

Figure 14. Clarion Clipperton Fracture Zone in the subtropical eastern Pacific Ocean.
(A) Map of the CCZ exploration claims and protected area. Image from International Seabed Authority.
(B) Bathysaura mollis *and brittle star. Image Credit: Diva Amon and Craig Smith, University of Hawaii*

For deep pelagic ecosystems, the project would help elucidate variability over time, assess responses to climate change, in deoxygenation, acidification and human activities (e.g., seabed mining and fishing), and address the consequences of changes in ecosystem structure due to OMZ intensification, thinning of the pelagic oxygenated zone, and ocean acidification.

Additionally, the demonstration project will focus on assessing the variability of environmental conditions (e.g., water velocity/benthic storms, turbidity, T, pH, O2, POC flux) in these abyssal ecosystems targeted for mining. Taking it a step further, this variation will be explored in terms of its influence on biodiversity and function of animals and microbes. These efforts will help to elucidate the functional importance of animals and microbes in abyssal ecosystems.

There are several synergies between this demonstration project and TPOS 2020. In its First Report[16], TPOS2020 recommends long-term moorings to observe the Inter-Tropical Convergence Zone (ITCZ) and trade winds at approximately 14 N, 124 W, and 14 N, 155 W. These locations encompass the intense and expanding OMZ of the eastern tropical Pacific, contain key fisheries populations, and are representative of some of the largest and most poorly studied benthic and midwater biogeographic provinces in the world ocean (Watling et al. 2013). These areas also fall within the core region of nodule-mining exploration claims registered with the ISA. This demonstration project will seek to estimate full-ocean-depth heat content anomalies on seasonal and longer time scales as well as detect changes in temperature and salinity characteristics on interannual to decadal timescale in the deep ocean in relation to high latitude water mass variability and formation rates. By adding additional observations to the area, the project will reduce the present 2000 m discontinuity in ocean observations for improvement of forecast model initialization and ocean data assimilation.

[16] http://tpos2020.org/first-report/

This demonstration project and resulting data could benefit at least 14 countries with seabed mining exploration claims in the CCZ, assist capacity building for those that are developing countries (e.g., Tonga or Nauru), create new collaborative opportunities which advance science diplomacy. DOOS studies around these CCZ locations could include long-term measurements in the benthic boundary layer and deep water column of the currents (ADCPs), vertical POC and mass flux (deep sediment traps), turbidity (sediment erosion/deposition), oxygen, pH, temperature, salinity, seafloor habitat conditions time lapse imaging of animal behavior, bioturbation, pelagic and benthic community structure/function biodiversity, benthic community oxygen consumption, and other key physical, geochemical, and biological parameters. Such observations would fundamentally advance our understanding of baseline functioning of ocean biogeochemical systems, and our ability to predict and evaluate the consequences of climate change in the future.

C. AZORES ARCHIPELAGO

The Azores is a volcanic archipelago located in the northeast Atlantic, above a tectonically active triple junction between the North American, Eurasian, and African plates, surrounded by abyssal plains deeper than 3000 m. The area has numerous seamounts, deep fracture zones, trenches, and a considerable extension of the Mid-Atlantic Ridge as well as abyssal areas. Located at the northeastern edge of the North Atlantic subtropical gyre, the oceanographic conditions in the region are influenced by the Atlantic Meridional Overturning (AMOC), which has been identified as an important, but poorly understood, element of the Earth's climate system (Amorin et al. 2017). In addition to the widespread hard and soft-bottom habitats, prominent vulnerable marine ecosystems in the region include deep-sea hydrothermal vents (Figure 15A), sponge aggregations, cold water coral gardens (Figure 15B) and reefs, and extensive fields of xenophyophores (Morato et al. 2016).

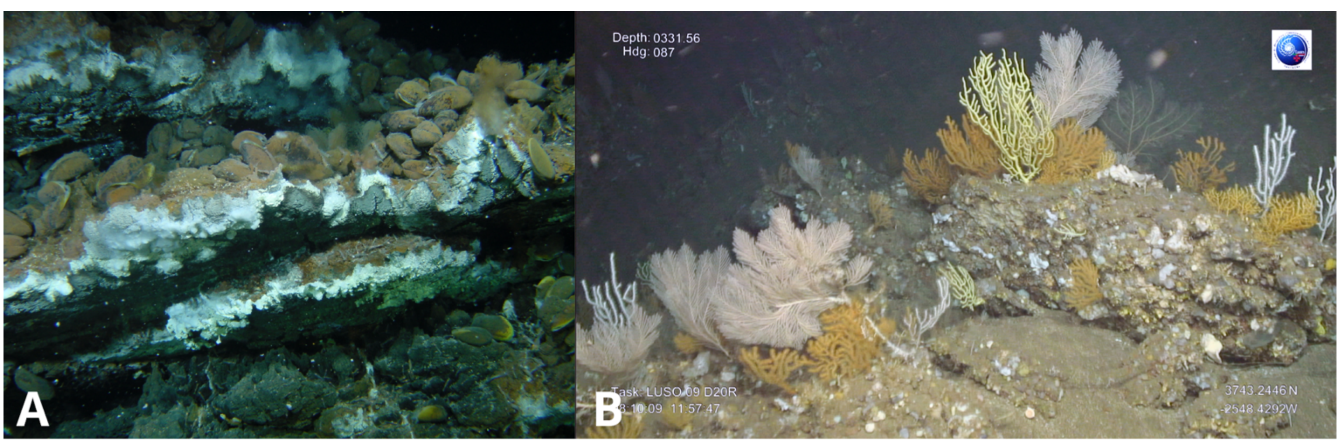

Figure 15. *Azores proposed demonstration site habitats. (A) Lucky Strike vent field marine protected area. (B) Coral garden dominated by the octocorals* Callogorgia verticillata*,* Acanthogorgia sp*. and* Dentomuricea c.f. meteor *at 332 m depth in the SW slope of São Miguel Island, Azores. Photo credits: Estrutura de Missão para a Extensão da Plataforma Continental - ROV Luso (EMEPC/Luso/Açores/2009).*

Because of its unique setting in the proximity of diverse open-ocean and deep-sea habitats, the Azores are a strategic location to test Biodiversity and Ecosystem EOVs that are still in the concept phase for the deep-ocean. These include collecting data on ecosystem functioning, connectivity, and biodiversity (taxonomic, functional diversity) at multiple scales, from bacteria to top predators, and from Atlantic basin (amphi-Atlantic population connectivity) to large-scale migrations. Additionally, important is the surveillance of biological communities, e.g., monitoring at changes in species ranges, community composition, structure and turnover, larval dispersal, as well as detection of potential invasive species, trophic interactions between benthic and pelagic communities, related to global environmental change.

As the Azores is an area of increased Blue Growth opportunity in the deep-sea (fishing, bio-prospecting and mining), this project offers the possibility of monitoring/testing EOVs under the cumulative impacts of global (warming, acidification, deoxygenation, changes in POC) as well as local (fishing, mining) stressors.

There are numerous infrastructure-related resources available in the Azores that could be integrated within the establishment of a demonstration site for deep-ocean observing. The Azores hosts two fixed-point observatories within the EMSO, with nodes at the Lucky Strike hydrothermal vent and, in the near future, a coral garden area in the Condor seamount. The observatories include numerous sensors (e.g. pH, temperature, salinity, oxygen, turbidity, ocean currents) to monitor the biogeochemical coupling of the benthos, water column, and atmosphere. Additionally, the area hosts an experimental laboratory to research scenarios of climate change on deep-sea organisms that includes a pressurized vessel with 20 liters' capacity that can simulate depth to 4000 m to conduct studies on the effect of environments under pressure. Other infrastructures available include remote platforms (e.g., vessels), receiving devices (and sources) for passive and/or active ocean acoustic tomography/thermometry, and instrumented marine mammals.

The enhancement of the existing fixed observatories in the area with sensors for the collection of long-term data on carbon/biogeochemistry variables (alkalinity, pH, pCO2, oxygen, inorganic nutrients) and ocean currents would provide much needed information on ocean change in relation to climate and AMOC patterns, possibly complementing other fixed monitoring sites in the North Atlantic. These fixed observatories would also offer an ideal setting to test new technology.

Mobile deep-sea laboratories host a wide range of relatively light-weight hydrographic, biogeochemical, optical and acoustic sensors for monitoring EOVs related to ecosystem functioning, as well as fixed biological survey equipment (e.g. benthic chambers, microprofilers, sediment traps, larval pumps). The mobility of these platforms would allow for the collection of information in a variety of ecosystems and under different impact scenarios, e.g., areas with or without fishing or mining, or in the proximity of land infrastructure.

Baseline monitoring of the deep seafloor is a global priority. However, the technology available requires the use of large ocean vessels and expensive technology. The Azores already has skilled human resources focused on seafloor mapping that could work with other partners to develop and test alternative technologies, such as unmanned vehicles that combine seafloor mapping, with the collection of physical-chemical and biological data for an integrated characterization of deep-sea communities and ecosystems.

The Azores offer a wide range of environmental conditions (e.g. corrosive conditions in hydrothermal vents, high pressure in abyssal areas) where the performance of technologies under development can be tested and then applied elsewhere in the world. The unique geographic, oceanographic, and biological characteristics of the Azores, together with the already existing infrastructures in the archipelago, make the Azores a key location for the proposed demonstration site for deep-ocean observing.

D. NORTHEAST PACIFIC (ONC/OOI)

The Cascadia Margin and Juan de Fuca Plate exemplify opportunities for technologically advanced interdisciplinary ocean observation. The coupling of the US NSF OOI Regional Cabled Array (RCA) and the ONC Neptune observatory provide unprecedented opportunities for an in-depth regional study with decadal time–series observations of globally significant oceanographic processes – including biogeochemical cycles, fisheries and climate forcing, tsunamis, ocean dynamics, carbon flux from the seafloor to the hydrosphere, life in extreme environments, and plate tectonic processes. The submarine cabled observatories span ocean depths from 25 m to 2900 m, include ~1700 km of high power and high bandwidth fiber optic cables, 14 subsea terminals, and more than 30 secondary junction boxes at key experimental sites. This infrastructure provides power and communication to hundreds of seafloor instruments and state-of-the-art moorings with instrumented profilers streaming data to shore at the speed of light. The OOI and ONC both support machine-to-machine interface cyberinfrastructure for real-time data access and download. Diverse users globally can download data from both arrays through the Internet.

The diverse environments and technologies covered by the OOI and ONC offer a strategic pilot site to demonstrate and evaluate EOV's needed to address key deep ocean science questions, across their required temporal and spatial measurement scales. The cabled biogeochemical and physical environments in this region span a continental margin strongly influenced by upwelling, widely contrasting pelagic and benthic physical and biological regimes, vigorously venting methane seep sites, the Cascadia Subduction Zone (Figure 16), active hydrothermal vents, and the most robust volcano on the Juan de Fuca Ridge Axial Seamount. The ONC array includes seismometers, a temperature resistivity probe and an array of moorings with CTD's and ADCPs' to quantify heat and flow of material along the ridge axis. The OOI RCA at Axial Seamount includes more than 20 geophysical, chemical and biological seafloor instruments and a suite of complementary instruments of two profiling moorings at the base of the volcano (Kelley et al. 2014).

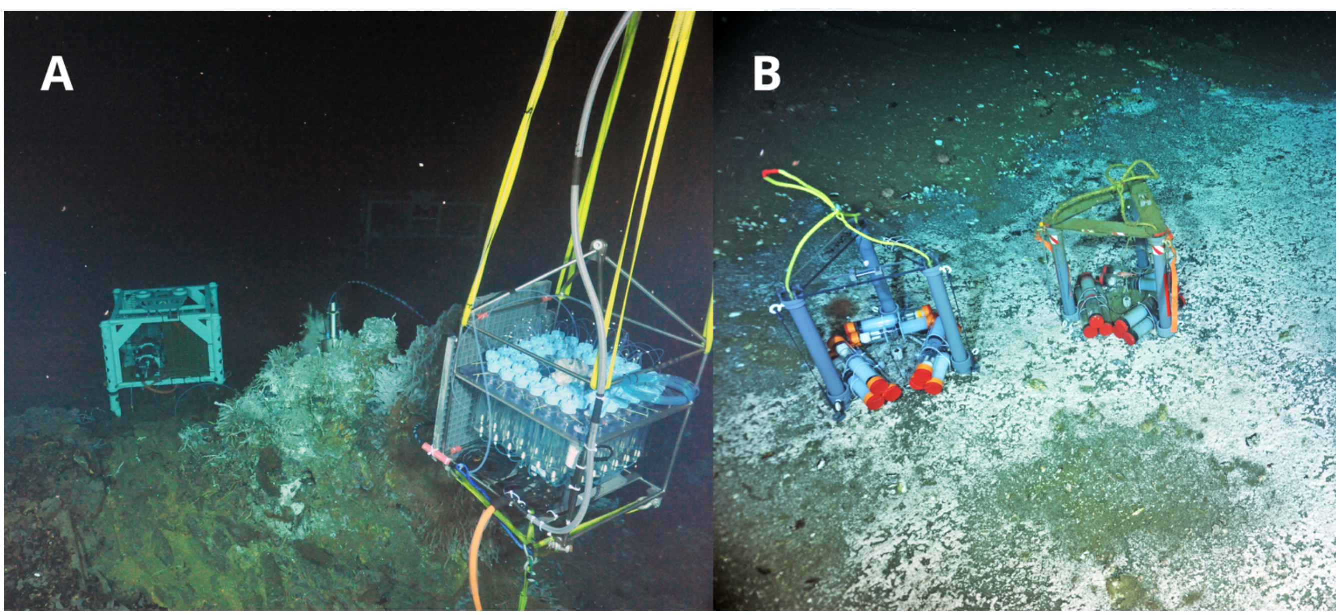

Figure 16. *OOI Cabled Instrumentation (A) International District Hydrothermal Field on Axial showing a cabled mass spectrometer, couple fluid-microbial DNA sampler with temperature, and a digital still camera at the El Gordo vent site. (B)Southern Hydrate Ridge: Cabled Array flow meters, mass spectrometer and osmotic fluid sampler. (Credit: NSF OOI)*

Along the coastal margin, the arrays encompass a complex system of currents where wind- and tide-forced motions promote turbulent mixing that influences transport and distribution of nutrients and biota. The highly biologically productive Pacific Northwest has experienced several locally- and globally-driven stressors, including increasing hypoxia and harmful algal blooms (Graham et al. 2004), along with clear impacts of ocean acidification. The CO_2 saturation values and shallowing of acidic waters currently observed in the area were not predicted to occur for another 50 years (Feely et al. 2008). These intertwined and complex physical, biological, and chemical processes respond to forcing on multiple spatial and temporal scales, strongly influenced both by La Nina and El Nino events and by shelf-slope interactions with the deep sea.

The OOI and ONC infrastructure offers opportunities available nowhere else in the ocean to examine key questions and processes operating at different spatial scales with parallel temporal EOV measurements. The NE Pacific infrastructure has no equal in providing diverse and sustained observations of the deep ocean. Measurements from hundreds of cabled instruments on the seafloor and throughout the water column provide an observational opportunity to advance ocean sciences, test and evaluate EOV's over space and time, and use these results to guide other DOOS and GOOS programs.

VIII. COORDINATION ACTIVITIES

A. CRITERIA OF A DOOS PROJECT

DOOS welcomes the opportunity to align with groups that are engaged with proposals, projects, or programs concerned with a greater understanding of the deep sea.

Box 4. CRITERIA OF A DOOS PROJECT

Groups are encouraged to state that they are in alignment with DOOS if they meet the following criteria:

- The project collects data in the deep sea (defined as generally >200 meters and preferably >2000 meters)
- The project addresses one or more of the DOOS science and/or societal questions.
- The project is aligned with the GOOS Framework for Ocean Observing, and measures one or more GOOS EOVs.
- The project makes collected environmental data freely and openly available in an established data repository (within 2 years of collection when feasible) and sends DOOS the link to those data when available. Exceptions can be requested for data of special concern (e.g. endangered species locations), but these must be described to DOOS in advance of DOOS endorsement.
- The project contributes to sustained deep-ocean observatories and/or large-scale, long-term understanding of the deep ocean. If the project is of local/regional scale, has a limited time frame (e.g., pilot study), or focuses on new technology development, it must identify its global contribution.

B. COMMUNICATION MECHANISMS AND USER ENGAGEMENT

DOOS has a unique opportunity to serve as a communication hub for a broad spectrum of the deep-ocean science community, and to an extended data and information user community. There is a growing need for cross-disciplinary information transfer among the physicists, biogeochemists, biologists, engineers, technology experts, data managers, law and policy specialists, social scientists addressing the deep ocean, and other deep ocean stakeholders (Section II.B.). DOOS seeks to organize and integrate different observing parties, projects, and networks as well as advocate for specific observing needs to funders. To this end, DOOS seeks to establish a subcommittee with liaisons from the major ocean-observing programs such as Core Argo, Deep Argo and BGC Argo, Go-SHIP, Ocean Sites, cabled observatories, and others (see Appendix A). This subcommittee will facilitate communication of outputs and new directions among programs and the broader scientific community.

The DOOS website[17] provides the core communication mechanism for the program to reach its user community. DOOS envisions that content on the website may include updates on deep observing programs, research calls and collaborative opportunities, engagement opportunities for the science community at upcoming scientific conferences and workshops, special themed journal issues, or cruise information. Additional communication mechanisms include townhall meetings, special sessions, or plenary presentations at scientific conferences, generation of white papers, publications in broad-spectrum venues, periodic online updates, materials made

[17] www.deepoceanobserving.org

available via the website (slides sets, fliers, graphics), and social media. DOOS will also engage with other deep-ocean projects and community communications arms (CLIVAR, DOSI, INDEEP, etc.) to establish and promote clear and comprehensive messaging.

Not only does a successful DOOS rely on communication to the scientific community, it also relies on open and transparent communication with the many decision-makers, and stakeholders across the globe. A periodic update will be disseminated to the DOOS-maintained mail list that addresses deep-sea updates on the following topics: new deep observing activities and opportunities, updates on large program activities and plans, data management, new observing publications, capacity-building, international policy, and DOOS activities.

C. CAPACITY BUILDING

1. CREATING PARTNERSHIPS

Existing capacity building training programs related to ocean observing could offer collaboration and partnership opportunities for DOOS to contribute to or build a dedicated deep-ocean training program. Today, two well established international groups focus on ocean observation capacity building and end-user engagement: the Partnership for Observation of the Global Oceans (POGO) and the GEO Blue Planet initiative.

Additionally, the UNESCO/IOC Oceanographic Data and Information Exchange (IODE) and WMO Learn Education and Training Program[18] (ETRP) have made continued efforts to facilitate access to a wide range of training materials. The Ocean Teacher Global Academy[19] initiative under the auspices of the IODE program allows training courses to take place simultaneously in multiple locations using video conferencing technology. The Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) from WMO and IOC has Capacity Development plans to empower developing States – particularly Least Developed Countries (LDCs) and Small Island Developing States (SIDS) by providing expert training on the applications of ocean observation data for understanding and predicting regional weather, ocean and climate.

DOOS will work with these groups to ensure that its efforts for capacity development and technology transfer are appropriately integrated into their programs and projects, and, to the degree possible, work to contribute observation guidance to efforts that relate to the deep-sea.

2. ENGAGING EARLY CAREER SCIENTISTS

Developing a strategy for deep-ocean observation requires attracting more students and early career scientists in related science and technology fields. This can be achieved by proving specific opportunities for early career scientists to engage with DOOS initiatives. Additionally, DOOS can identify training needs and opportunities in data management, technology innovation, and transfer that emphasize broad disciplinary scope and interdisciplinary science (e.g. biology-physics or ecology-geology interfaces, big data, sensors).

DOOS can act as a hub (possibly via its web platform) to support existing programs, for example through disseminating available berth offers or training internships of relevance to deep-sea observation, to which early career scientists (or students) could apply and receive support. For example, funding support for early career

[18] http://learn.wmo.int/

[19] http://www.oceanteacher.org/

scientists of developing countries and countries with economies in transition can be requested from POGO-SCOR Visiting Fellowships Program[20]. The grant covers a 1-3 month visit to another oceanographic institute and training on any aspect of oceanographic observation, analyses, and interpretation. Additionally, through specific courses and training programs through the Centre of Excellence in Observational Oceanography[21], POGO provides training and technology transfer to emerging economies, and builds awareness of future challenges. InterRidge also offers visiting grants and cruise bursaries for early career scientists (from geophysics to ecology). The ISA Endowment Fund for the InterRidge Student and Postdoctoral Fellowship Program for collaborative marine scientific research is also supporting the participation of qualified scientists and technical personnel from developing countries.

3. ENGAGING THE PUBLIC

The sense of exploration and otherworldliness that comes when describing deep ocean research provides a unique opportunity to inspire and inform the public about this area of oceanographic research. DOOS could support production of education materials (books, factsheets, tutorials, e-learning) to disseminate scientific advances to scholars and students. By developing outreach events and ocean literacy material DOOS could target school children and local communities and emphasize the importance of the deep ocean contribution to the prosperity and well-being of humanity. DOOS also can work with other organizations to disseminate k opportunities to participate in expeditions via telepresence (e.g., via NOAA's office of Ocean Exploration and Research, the Ocean Exploration Trust, or the Schmidt Ocean Institute).

D. POLICY LINKAGES

The vision of the DOOS Project is to help develop an enduring, globally integrated network of systems that can help support strong science, policy, and planning for sustainable oceans. There are realized and potential impacts in the deep ocean from both local human stressors, (e.g., fisheries, shipping, energy extraction, and deep seabed mineral mining) as well as global stressors, (e.g., climate change and pollution). In order to fully understand the interaction between, and the cumulative impacts of, these different stressors, comprehensive monitoring is needed. This will in turn inform integrative and adaptive management measures to ensure the long-term sustainability of both critical deep ocean ecosystems and industry.

The international bodies and initiatives where input from sustained deep-ocean observations would be most relevant include:

- **United Nations Framework Convention on Climate Change (UNFCCC) and Paris Agreement:** The UNFCCC Conference of Parties meets every year amidst a growing need to incorporate ocean issues into government commitments. Avenues for input include: 1) Ocean & Climate Initiatives Alliance (OICA-science) acting to unite parallel and ongoing initiatives under a joint action framework to drive momentum for concrete ocean-based solutions in the implementation of mitigation and adaptation measures. DOOS contributes to OICA via the Deep-Ocean Mitigation and Adaptation Initiative; 2) the Ocean Pathway Partnership which aims to increase ocean considerations in the UNFCCC process and action in priority areas impacting or impacted by

[20] http://ocean-partners.org/pogo-scor-fellowship
[21] http://www.ocean-partners.org/training-education

ocean and climate change; and via these 3) the Talanoa Dialogue for climate ambition - a global conversation about efforts to combat climate change in which Parties and non-Party stakeholders are invited to engage.

- **Intergovernmental Panel on Climate Change (IPCC):** DOOS input to IPCC, the science arm of the UNFCCC, can come through contributions to Assessment Reports (e.g., upcoming AR6) and special reports. Deep-ocean processes and ecosystems are increasingly acknowledged and discussed in these reports. DOOS scientists should participate as authors and reviewers to the extent possible.
- **The UN Decade of Ocean Science for Sustainable Development 2021-2030:** The United Nations, under the leadership of the Intergovernmental Oceanographic Commission (IOC) has agreed to launch a globally coordinated program to focus on science needs to implement SDG 14. An implementation plan will be under development from 2018-2020, with the goal of launch in 2021. Sustained ocean observations are already being considered as part of the plans, thus there will be a need to coordinate DOOS plans with the IOC, ideally through GOOS engagement.
- **Voluntary Commitments to help implement SDG 14:** DOOS/DOSI/INDEEP submitted a set of voluntary commitments to advance science for deep ocean sustainability that will require continued outreach, reporting, and follow-up. Deliverables include facilitating monitoring of the status and health of the deep ocean and its biodiversity by: 1) contributing to the definition of essential ocean variables (EOVs); 2) facilitating development of new deep-ocean observing technologies; 3) building stable, long-term support for deep-ocean observing; and 4) supporting coordination of existing deep-ocean observing programs across regions and disciplines.
- **UN Intergovernmental Conference to negotiate the new Biodiversity Beyond National Jurisdiction (BBNJ):** Meetings will take place at least four times between 2018 and 2020 to negotiate the BBNJ. This negotiation process provides an opportunity to profile the importance of DOOS and sustained deep-ocean observations for biodiversity, conservation, and sustainable use. Including area-based management and environmental assessment tools, as well as an understanding of cumulative impacts including from pollution and climate change-related effects. A transfer clearinghouse for data, projects, and technology will most likely be one of the outcomes of the BBNJ.
- **International Seabed Authority:** The ISA meets twice a year while the deep-sea mining regulations are under development. The meetings, and associated expert workshops, provide an opportunity to underscore the importance of integrated deep-ocean ecosystem monitoring and the need to include ecological and biological variables relevant to monitoring changes due to climate change and seabed mining. The proposed DOOS demonstration project in the Clarion Clipperton Zone could help advance monitoring science and technology and provide helpful input on what needs to be included in monitoring requirements.
- **The UN Food and Agriculture Organization's (FAO) Committee on Fisheries (COFI):** COFI meets every other year to look at global and regional fishery trends, make recommendations for fisheries policy, and set FAO's research agenda. Deep-ocean observations will be vital to inform not just changes affecting the sustainability of deep-sea fisheries and habitats, but also ecosystem shifts affecting pelagic fisheries and any future mesopelagic fisheries. In December 2016, UNGA Res. 71/123 (para. 185)[22] called upon States and Regional Fisheries Management Organizations (RFMOs) to "take into account the potential impacts of climate change and ocean acidification in taking measures to manage deep-sea fisheries and protect vulnerable marine

[22] https://www.un.org/en/ga/71/resolutions.shtml

ecosystems". DOOS can join DOSI in working with the FAO to advance research that examines climate impacts on deep-sea habitats, fish and fisheries and viable management solutions.

- **The UN Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including socio-economic aspects:** The First Global Integrated Marine Assessment (World Ocean Assessment-1) demonstrated the need for sustained ocean observations to monitor and understand ocean change. The second integrated ocean assessment process is now underway, which will include a series of regional workshops and request for input from a pool of experts. With the emphasis of WOA-2 on recent changes in knowledge and human activities relative to ocean sustainability, strong deep-ocean representation will help identify knowledge gaps and research needs relative to deep-ocean observing.
- **International Maritime Organization (IMO):** The IMO and its scientific arm, the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), examine issues related to inputs of contaminants in the ocean such as from ships, mine waste, and are increasingly concerned with CO_2, nitrogen and geoengineering. DOOS engagement with GESAMP will ensure sufficient consideration of deep-ocean processes and responses.
- **Convention on Biological Diversity (CBD):** The CBD has described through a series of regional expert workshops over 400 Ecologically and Biologically Significant Areas in need of enhanced protection and management throughout the world ocean. Many of these areas include the deep-ocean. DOOS engagement may advance understanding and monitoring of these areas and contribute to dialogue on biodiversity maintenance.
- **European Commission:** The European Commission has funded various research and monitoring projects, including Managing Impacts of Deep-seA reSource exploitation (MIDAS), which investigated the impacts of deep seabed mining; AtlantOS, which is putting together a template for sustained ocean observation across the Atlantic Basin; and SenseOcean, which is working to develop a marine biogeochemical system for monitoring the health of the ocean. Horizon 2020 is supporting a project called "Integrated Assessment of Atlantic Marine Ecosystems in Space and Time" (iAtlantic). The proposed DOOS demonstration project in the Azores may be able to link key deep-ocean observations to these efforts.
- **National/regional science projects:** States in the European Union have funded deep-ocean projects including Joint Programming Initiative (JPI) Oceans on the Ecological Impacts of mining. A second phase of this JPI Oceans project will focus on deep-sea mining generated plumes, which could have ties to the DOOS demonstration project in the CCZ.
- **G7 Science ministers:** The G7 meeting provides an ongoing opportunity to advocate for enhanced ocean observing coordination and monitoring.

Other opportunities will arise at the global and regional level as countries seek to grapple with the cause and consequences of rising CO_2 impacts on land and at sea.

IX. MOVING FORWARD

The DOOS Project is helping lay the foundation for an international framework for sustained observation of the deep ocean over the next decade with a view to the next half-century. In the near term, the OceanObs ’19 meeting will be a key milestone in the strategy goals for DOOS. Involvement in the meeting and future activities include the documenting of DOOS contributor advice on EOV identification and specification, data management, demonstration projects, and other activities outlined in this Implementation Guide (Figure 17). Additionally, in the near term, the DOOS project will seek ways in which regional observatories can be brought together to collaborate and coordinate efforts in order to address global-scale questions. For example, one outcome of this could be a federated global observing system from an existing collection of regional and local efforts.

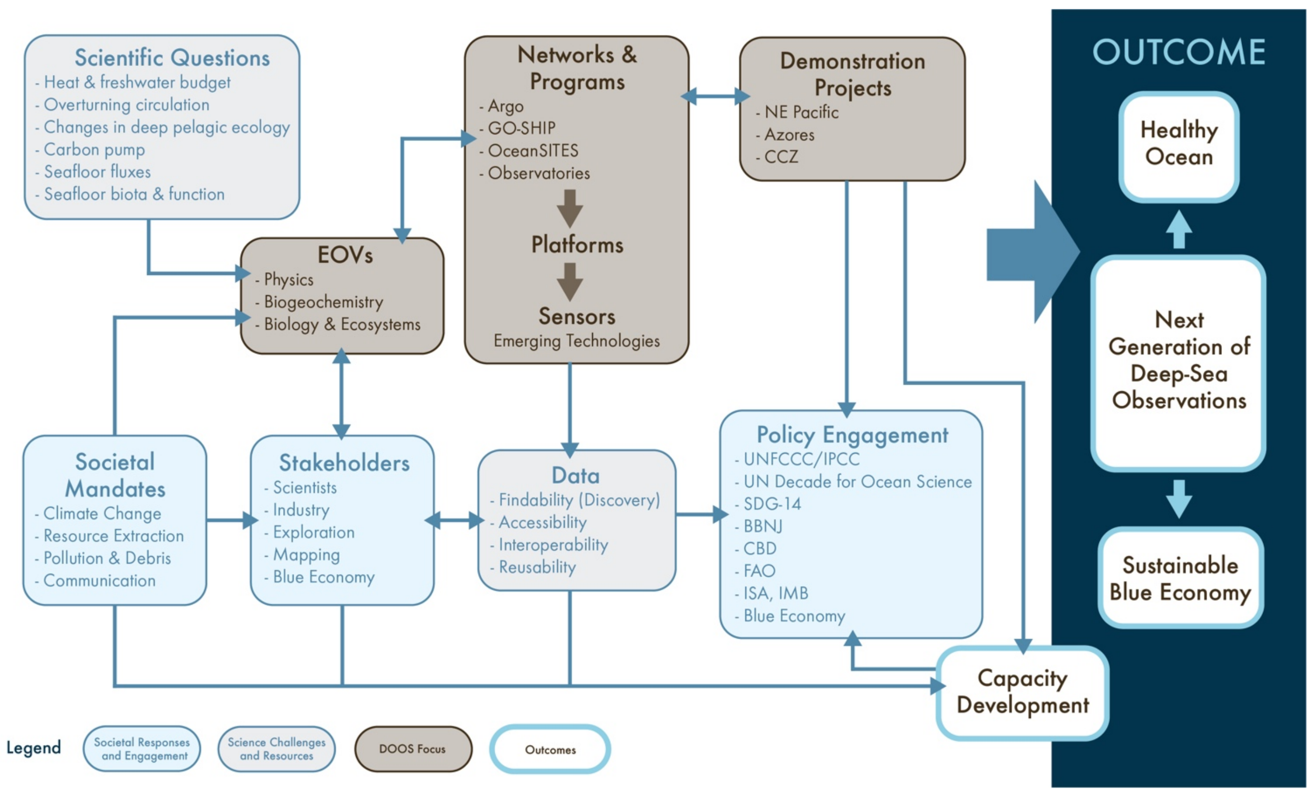

Figure 17. *The key components of a deep-ocean observing strategy designed to promote healthy oceans and sustainable blue economy (from Levin et al. in press).*

In this effort of coordination and collaboration, DOOS will liaise with major observing programs to seek opportunities for improving deep-ocean observing capability. Its data team will leverage observing asset inventories and emerging cyberinfrastructure to improve access to existing but widely distributed infrastructure and data initiatives. Specific outcome objectives include: international engagement from the major disciplines already identified by GOOS; production of a white paper and accompanying publication on deep observing goals and needs (Levin et al. *in press*); and initiation of one or more demonstration projects that illustrate the power of cross-disciplinary observation in the deep ocean, with an emphasis on observing approaches that may be scalable to global observing needs. DOOS outcomes will mark an important evolution for GOOS, where issues specific to deep-ocean observing can be addressed in a coordinated way across the globe.

Over the next few years, DOOS will work to build global scientific capacity to address SDG 14 targets as they relate to the deep ocean. This will involve cooperation with DOSI and INDEEP to increase scientific knowledge, develop skills and harness technology to address current and expected human impacts, including those related to climate change. Key aims include the advancement of an understanding of deep-ocean ecosystems within and beyond national jurisdictions in order to facilitate the achievement of SDG Targets 14.2, 14.3, 14.5, 14.7, 14.a and 14.c. DOOS will facilitate delivery of voluntary commitments to achieve SDG 14 in 2017 to:

- Promote easy and open access to essential deep ocean observations (physics, biogeochemistry, biology and ecosystems) and enable research to further the understanding of baseline conditions in the deep ocean and inform ecosystem-based management and spatial planning through space and time.
- Work with the UNESCO/IOC, DOSI and INDEEP to facilitate monitoring of the status and health of the deep ocean and its biodiversity by: 1) contributing to the definition of essential ocean variables (EOVs); 2) facilitating development of new deep-ocean observing technologies; 3) building stable, long-term support for deep-ocean observing; 4) supporting coordination of existing deep-ocean observing programs.
- Enhance deep-ocean data accessibility globally through promoting the FAIR (findable, accessible, interoperable, reusable) principles. Among the many benefits will be the expansion of scientific and technical capacity for managing deep-ocean ecosystems among Small Island Developing States and least developed countries by 2025.

Box 5. SUMMARY OF DOOS RECOMMENDATIONS

1. Define Deep Ocean EOVs, create or improve specifications, and integrate these into GOOS EOV panel deliberations.
2. Identify and develop expanded and enhanced deep-ocean observing capabilities (e.g., through more efficient use of vessel servicing platforms and collaborations with industry). Mainstream deep-observing into the Decade for Ocean Science for Sustainable Development.
3. Develop an advanced cyberinfrastructure for better data mining, integration, and FAIR (findability, accessibility, interoperability, reusability) across the three main disciplines.
4. Identify deep-ocean data gaps and needs through gap analysis, communicate these to appropriate large program leads and the broader science community.
5. Initiate a committee of large program deep observing leads to communicate and coordinate observing activities among programs and to the broader scientific community.
6. Expand, update, and maintain a deep-ocean observing inventory, facilitating access to program metadata.
7. Develop demonstration projects that address questions of scientific and societal significance, integrate observing across disciplines, act to help mature observing technologies, and provide a template for future observing efforts.
8. Develop communication tools to inform the science community and convey deep-ocean observing needs and advances across disciplines, regions, sectors and jurisdictions.
9. Develop or improve connections to stakeholders, in particular in the economic and political sector to raise support for and sharpen requirements of DOOS.

Lastly, DOOS will strive to play a major role in the advocacy for and coordination of deep-ocean observing in the context of sustainability under the Decade for Ocean Science (2021-2030). DOOS will innovate in defining next generation questions, technologies, observing strategies and data infrastructure for the Decade. Just as themes of climate change, ocean acidification and ocean deoxygenation were barely on the scientific radar 25 years ago, the next quarter century is likely to see observations on new time and space scales, at new levels of biological organization (from sequences, enzymes and molecules to ecosystems), and of new phenomena (e.g., microplastics, unexpected contaminants, animal migrations). It is the hope and aim of DOOS that observations of the deep ocean play a large part in these advances and new directions over the next quarter century and beyond.

DOOS is currently examining several of these potential new directions in ocean observation:

- Understanding the value of ocean observing for industrial operations to advance technology and discover untapped data repositories,
- Working directly with UN agencies responsible for managing resources or protected areas in the deep ocean and enhancing deep-sea citizen science,
- Enhancing education and training programs,
- Facilitating data curation,
- Enhancing a data clearinghouse and the development of new data handling tools.

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APPENDIX A: SUPPORTING ACTIONS

Note: These are meant to be 12-18 month actions from the time of the report's release in May 2019. For more background on these specific items, please reference the associated section within the text.

Societal Motivation and Science Challenges Actions (Sections I.C and III):
- Support DOOS SC and TT member attendance at related meetings and sessions conducted by physical oceanography and solid earth expert groups and teams also aligned with DOOS and GOOS principles.
- Support DOOS SC and TT member attendance at related meetings and sessions conducted by biogeochemistry expert groups and teams also aligned with DOOS and GOOS principles.

Global Project Participation Action (Section I.B):
- Support ongoing participation of DOOS leadership in meetings of GOOS (specifically its panels and coordination activities related to large networks), POGO, BluePlanet, DOSI, INDEEP, the UN Decade for Ocean Science, and others.

EOV Actions (Sections I.C and III):
- Coordinate and align Deep -EOVs with GOOS panel EOV designation (especially biology where the greatest discrepancy exists in EOVs) by actively encouraging and funding DOOS steering committee, task team members, and other practitioner attendance at GOOS and other relevant meetings and workshops.
- Support workshops exploring means to achieve the conceptual, technical, and data integration of EOVs across disciplines via demonstration projects, tackling emergent, inherently cross-disciplinary themes such as productivity, connectivity, and response to climate change.
- Compile a list of standard ocean variables (SOV), defined as measurements that are routinely collected in domain-specific, regional, or platform-dependent science operations that support the use and interpretation of EOVs.

Platform and Sensor Actions (Section IV):
- Conduct a study of the readiness levels of technologies (sensors and platforms) at various depths as related to DOOS EOV measurements and associated challenges to data integration.
- Incorporate recommendations from OceanObs '19 to facilitate the integration of deep-sea platform needs of the physics, biogeochemistry and biology disciplines, making them more technologically and data-output compatible, and cost-effective for each discipline. From these develop a program that identifies EOV integration approaches and the depth-specific readiness levels of technologies related to DOOS EOV measurements and associated challenges to data integration.

Data and Cyberinfrastructure Action (Section V):
- Support activities to define data curation, access, and user best practices and maturation or standardization requirements across deep-sea EOVs and associated data uptake and product development communities.

Coordination Activities Action (Section VII):
- A more systematic inventory of the type of training with a deep ocean theme should be compiled and made available on the website. Existing training courses and associated funding support dedicated to deep ocean science and technology or focusing on observation with a large deep-sea component, could be compiled and

advertised to a wider international audience through the DOOS website other outreach activities. This includes 'summer schools' or training workshops, other student opportunities (e.g. internships), and possible funding support under INDEEP, DOSI, IODP, InterRidge, specific EU-funded programs. This portal could include a review of academic institutions offering opportunities for students to join regular courses and MOOC.

Moving Forward Action (Section IX):

- Hold a post OceanObs '19 Conference open community workshop or scientific session and reinforce or expand task teams to advance (a) deep-ocean relevant EOV development and dissemination (b) deep observing coordination – especially among the large programs (c) input to science planning and international policy (d) capacity building and training in deep-ocean observing.