The Deep Ocean Observing Strategy (DOOS) contribution to the Decade for Ocean Science for Sustainable Development Science Action Plan

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I. Knowledge Gaps, Scientific Questions and Priorities

The deep sea covers over half the planet and much of the habitable area, yet remains the least observed part of the ocean. The IPCC 2019 Special Report on Ocean and Cryosphere in a Changing Climate[1] highlights major knowledge gaps relevant to the deep ocean that can guide observing plans for the next decade. To address uncertainties in the timing, magnitude and patterns of the projected changes in climate variables we need (a) expansion of deep ocean temperature and salinity observations for sea-level and closure of the energy budget, (b) oxygen and carbon measurements dense enough to quantify de-oxygenation of the world ocean and track the mechanisms driving the ocean carbon cycle, and improved understanding of (c) deep processes that affect ocean productivity, and (d) the interactive effects of multiple climate drivers on ecosystems. Ecological and environmental data are needed to inform particle flux, food web, habitat suitability and connectivity models that can address ecosystem response to both climate and direct human disturbances in the deep sea.

Through a series of scoping activities, the community engaged in the Deep-Ocean Observing Strategy (DOOS) under the auspices of the Global Ocean Observing System (GOOS) identified the most pressing observing needs[2]. For the **physical realm** DOOS prioritized the heat and inventory of the Earth system, especially below 2000m. In addition to deep Argo, smart cables, deep moorings, landers, cabled observatories, other oceanographic and industrial platforms are required. Time series obtained with instruments calibrated pre- and post-deployment and high-quality shipboard observations will be essential to resolve temporal variability and establish accurate observations from mobile and disposable platforms. Improved understanding of the role of the deep ocean in global heat, salt and freshwater budgets will require knowledge of the processes at the water column-seafloor boundaries and distribution by deep ocean transport and mixing, both of which are influenced by bottom topography. Time series at key sites and full mapping of the seabed (including subduction zones, mid ocean ridges and hot vents) will contribute to these goals. Availability of deep hydrographic observations is essential to improve how models represent connectivity to the deep ocean.

Understanding the global carbon cycle and its interrelationship with climate change hinges upon improved quantification of biogeochemical changes in the deep ocean, particularly over centennial and longer timescales. Key **biogeochemical questions** include the ability of the deep ocean to store carbon, and the roles of respiration and remineralization. These questions are linked to carbon

[1] IPCC. (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Chapter 5: Nathaniel L. Bindoff William W. L. Cheung James G. Kairo et al.

[2] Details are provided in the DOOS Science and Implementation Guide and in the community white paper by Levin et al. (2019) (available at www.deepoceanobserving.org).

inventories and fluxes, ocean acidification, the biological and solubility carbon pump, deoxygenation and nutrient dynamics, the vertical fluxes of particulate organic carbon in deep water, and their effect on- and influence from life in the deep sea. Contributions from BGC Argo, time series observations of detritus deposition, and respiration rates at the seafloor (via stationary or mobile benthic platforms) are needed to constrain the supply, and fate of organic matter. Additional gaps include understanding of climate change influences on the nitrogen cycle, denitrification, and productivity and on seafloor fluid and gas fluxes (e.g. methane) that influence stability of margin sediments and infrastructure. Intensified observations of areas of declining oxygen (eastern Tropical Pacific, Southern Ocean, NE Pacific) are required to constrain models and provide the mechanistic understanding needed to address model-observation discrepancies in deep-ocean oxygenation.

The **biological/ecological realm** is the least known in the deep ocean, particularly with respect to the diversity and distribution of organisms in the deep sea and the relationships among biodiversity, functional groups, and ecosystem services. Assessment of climate change consequences and the impact of multiple stressors, as well as the assessment of impacts from direct anthropogenic impacts (e.g., fishing, oil and gas extraction, deep seabed mining) requires this information. Key information gaps include temporal (natural) variability, interaction with mesoscale circulation, the influence of topography, environmental tolerances and thresholds, and sensitivity to food supply. Co-located environmental measurements, for example from moorings and benthic observatories, repeat hydrography, floats, AUVs and ROVs employing observations and biological sampling and potentially also eDNA, can start to address these questions.

II. Addressing the Gaps: Deep Ocean Observing Priorities and Goals

Goal 1. Extend deep-ocean observing capacities to the global scale as part of the UN Decade – addressing all deep-ocean-relevant Essential Ocean Variables and building on existing assets and networks.

A major DOOS task for the Decade will be to increase observing capacities in the deep ocean including the deep seafloor and sub seafloor in terms of spatiotemporal coverage and variables addressed. This can be accomplished in part through expansion to global scale of Deep Argo and BGC Argo, but requires critical support for calibration, validation and reference from shipboard sampling and repeat hydrography cruises. Deep Argo observations of full-depth temperature, salinity, and ocean currents will reduce uncertainties of the oceanic contribution to Earth's energy imbalance, improve our understanding of regional and global sea level change, resolve the spatial structure and seasonal-to-interannual fluctuations of the deep-ocean circulation, and increase accuracy of ocean-climate model predictions. BGC Argo's additions to the core Argo program of oxygen, nitrate, pH, downwelling light, chlorophyll fluorescence and optical backscattering will provide global and seasonal information relevant to ocean carbon uptake, deoxygenation, acidification, and productivity. By extending Argo into deep water, equipping a portion of the core Argo array with biogeochemical sensors and deep Argo floats with O_2 and pH sensors (when capable), the next decade can host the first fully global oxygen and carbon networks, offering an important large-scale, sustained framework for addressing the health of the ocean.

Additionally, the global ocean observing system lacks a solid Earth component, a gap not covered by the current set of GOOS EOVs. Observations of ocean bottom pressure, bottom fluxes (heat, salt, water, oxygen, and methane), organic matter availability and biological characterizations are proposed to inform geodynamics, sea level change, deep-ocean circulation and transport, the sequestration of carbon dioxide from the atmosphere, biodiversity maintenance, and the provision of critical ecosystem services. Building observation capacities at the deep seafloor will complement Decade activities focusing on an ocean-wide mapping of bathymetry (Seabed 2030) as well as habitats, animal communities and their functions (see DOSI submission to Decade).

Where possible, expanded deep-ocean observing will build on existing observation networks. In addition to the expansion of Deep Argo and BGC Argo arrays, DOOS will join forces with DOSI to advance deep-ocean and seafloor observations that incorporate biological communities and biogeochemical processes, e.g., by means of benthic crawlers, time-lapse photography, benthic imaging surveys, and sampling at OceanSITES stations. Further, DOOS will work to incorporate biological measurements that address multiple trophic levels as well as their diversity and functions into GO-SHIP, and strengthen new networks and the development of novel technologies that are needed for comprehensive, deep-ocean observation (e.g., smart cables, biogeochemical gliders).

In order to design and prioritize deep-ocean observing activities to be implemented as part of the Decade, DOOS is engaging with modelers, observing networks, deep-ocean experts and other stakeholders of deep ocean observation and stewardship.

Goal 2. Focus observations to meet requirements for ocean modeling.

Efforts to simulate deep ocean properties using global ocean general circulation models as part of climate or Earth system models face many challenges. These challenges include the extreme scarcity of deep ocean observations, the difficulty of existing global climate models to robustly represent the dominant processes leading to deep and abyssal water mass formation, the biases introduced by the notion of ocean model "spin-up" to equilibrium, neglect of the transient nature of the deep ocean in accumulating surface perturbations from climatic forcing, and neglect of bottom-intensified mixing, along with its impact on deep-ocean circulation. Uncertainties are exacerbated for BGC and ecosystem models, because of a lack of knowledge of mathematical principles to simulate these components.

DOOS will bring together the modeling and observing communities to meet these challenges. Modeling experts such as the CLIVAR Ocean Model Development Panel (OMDP) and the CLIVAR Global Synthesis and Observations Panel (GSOP), need to develop requirements for deep and abyssal ocean observations that can provide meaningful constraints for ocean models, and to define protocols (algorithms, data usage, and sharing) for model calibration and validation. These efforts will need to entrain existing large observational programs, such as GO-SHIP, Argo, Deep-Argo, BGC Argo, OceanSites, and other initiatives. Optimal use of observations of oceanic tracers, such as those collected by the GEOTRACES project, and in the future by BGC-Argo, for constraining the ocean's deep circulation critically depends on extending such efforts to coupled physical and biogeochemical models. Formal model calibration approaches, such as Bayesian inverse methods, need to be implemented, to optimally use the diverse but heterogeneous and spatiotemporally sparse observations to constrain and calibrate ocean models.

The extension of human impact in the deep sea necessitates the maturation of model frameworks that are formed, parameterized and validated by datasets that include deep-sea ecosystems across productivity regimes and seafloor habitat features. ***DOOS will develop a strategy to enable the evolution of ecosystem modelling, including deep-ocean processes.*** Special focus should be on the identification of essential ocean variables that can inform the collection of new observations and provide a means to integrate information into comprehensive spatial and temporal management tools[3]. For example, more comprehensive adoption of model forms that already exist for particle and biological energy tracking, size specific biomass, or biodiversity levels can inform the management of areas beyond national jurisdiction.

Goal 3. Improve standardization of and access to deep ocean observing data, samples, models, and derived products.

The impact of deep observing on science and societal goals relies on accessibility, searchability, and usability of data, samples, models, code, and derived information products to the widest possible community. ***DOOS proposes a three-pronged action plan for increasing the availability and impact of deep ocean information during the Decade that leverages and extends existing cyberinfrastructure.***

A. *Engage the deep observing community to increase the sharing and accessibility of deep-ocean data*

First, DOOS will develop short lists of best practices for data, samples, and models/code from existing resources (FAIR data, CoreTrustSeal, OceanBestPractices, Research Data Alliance, etc.), and promote and socialize these practices in deep observing communities in order to improve adoption. Rather than developing comprehensive approaches, these efforts will focus on a small set of practices that will achieve the greatest impact on deep data availability and usability. Best Practices adopted by DOOS will include standardization and sharing of methods for deep ocean observations and for quantitative assessments of the uncertainties in the data; they will incorporate sampling strategies, pre- and post-deployment calibration procedures, intercomparisons against other platforms, and data quality analysis procedures.

In support of this endeavor, the best practices for data will be reformulated as a list of requirements for DOOS data certification, i.e. characteristics that a deep data provider must have to earn a DOOS 'accreditation' for their data practices. This will be separated into "Discovery, Access, and Preservation" requirements, and "Data Analysis Readiness" requirements. The former will be related to having open, well-described data in stable repositories that participate in current discovery methods (e.g. repository registries). The latter is related to having self-describing, machine-readable data and metadata in standard, citable formats, to promote use to modeling and interdisciplinary studies. DOOS will help develop an appropriate mechanism for accreditation,

[3] Danovaro R., Fanelli E., Aguzzi J., Carugati L., Corinaldesi C., Dell'Anno A., Gjerde K., Jamieson A.J., Kark S., McClain C., Levin L.A., Levin N., Ramirez-Llodra E., Ruhl H., Smith C.R., Snelgrove P.V.R., Thomsen L. Van Dover C., Yasuhara M. **Ecological variables for developing a global deep-ocean monitoring and conservation strategy. Nature Ecology & Evolution. In revision.**

especially for non-government data sources in collaboration with GOOS Regional Alliances and in coordination with developing deep-ocean databases (e.g., OBIS, DeepData - International Seabed Authority, InterRidge Vent Database) and the IOC.

B. *Communicate deep ocean data, sample, and model/code requirements to improve existing cyberinfrastructure.*

DOOS will solicit data to fill gaps from the deep observation and modeling community, and engage with the governance bodies of existing repositories, standards, vocabularies and other tools to advocate for better support for deep resources. Examples include appropriate habitat classification, searching for data by depth in the water column, and precision/uncertainty descriptions appropriate to deep-sea environments.

C. *Develop interdisciplinary partnerships to identify and produce data products to increase societal impact.*

The development of data products that are useful and tractable with the currently limited data resources require iterative discussion among the stakeholders who require products, scientists who understand the data, technical staff familiar with the repositories holding the data, and modelers and/or data analysts able to work with the data. The challenge is to identify directly useful products that are tractable given current limited data resources. ***DOOS will lead an initiative to create working groups to develop information products to support key policy or management needs, while building capacity for use in developing countries***.

Goal 4. Facilitate partnerships, collaboration, integration and capacity building across deep-ocean observing communities, including deep-ocean exploration, seafloor mapping and private sectors, through the Deep Ocean Observing Strategy.

Building a globally integrated deep ocean observing system of systems that provides data to address ocean change and its consequences requires harmonized contributions from all deep-ocean practitioners. To achieve the above observing goals in an integrated fashion, DOOS plans to leverage common observing platforms, networks, and infrastructure through partnerships. ***DOOS will build communities of practice and networking that link existing science-based deep-ocean (and relevant space) observing networks, programs, and projects to data integration and sharing programs.*** This will involve engagement of JCOMM, GO-SHIP, ARGO/DeepARGO, BGC ARGO, OceanSITES, SOOS, TPOS, AtlantOS, GO-AN, GO_2NE, Observatories, NASA, COPERNICUS, MGDS and more.

Regional demonstration projects that promote end to end integration of stakeholders will be developed by DOOS to create a template for network integration and develop the next generation of integrated observing. The Clarion-Clipperton Zone (E. subtropical Pacific), the Azores Archipelago and the NE Pacific (OOI/ONC) are under consideration as demonstration projects. In developing these, and in pursuit of Goals 1-3, DOOS will reach out to the deep-ocean elements of the exploration (e.g. NOAA OER, OET, Schmidt Ocean Institute) and seafloor mapping GEBCO 2030) communities, scientific networks (GOOS, DOSI, INDEEP, MBON, RIDGE, DSBS), the energy, cable, deep fishing and mining industries (e.g., SERPENT, International Seabed Authority, Pacific Commission), as well as the conservation, biodiversity and relevant policy communities (e.g., Deep Sea Conservation Coalition, BBNJ, IPCC, GESAMP). The DOOS efforts will collaborate closely with the Ocean Exploration community. Exploratory work reveals unexpected phenomena that merit further study through monitoring efforts, and data collected through exploration initiatives can provide information critical for establishing long-term monitoring.

III. *Cross-cutting themes*

DOOS Goals 1-4 above will embrace capacity building. Partnerships will define a successful global deep-ocean observing strategy (Goal 4). Data and information access is a key objective of Goals 3 and 4. DOOS efforts will also prioritize communication and awareness raising among the data generator and user communities. In the coming decade DOOS plans workshops, town halls, creation of a network of networks, engagement with major funders, and public engagement through partnerships, as vehicles of action.

IV. Potential commitment(s) of DOOS to the preparation for and implementation of the Decade.

1. Identify, develop, or improve specifications for Essential Ocean Variables suitable for addressing scientific and societal questions in the deep ocean.
2. Develop and implement demonstration projects in the Clarion-Clipperton Zone, Azores and NE Pacific that bring together different observing communities (exploration, industry, academic), platforms and sensors to provide a template for global observing in the deep ocean.
3. Facilitate communication within the deep ocean science community (e.g., via major AGU or EGU Meeting Townhalls), engagement with the public (e.g., via NOAA OER).
4. Create a network of deep networks to achieve the goals above (e.g., via AccelNET proposal to National Science Foundation).
5. Facilitate FAIR data principles, codify best practices, and develop a data accreditation process for deep ocean data.
6. Collaborate with the Deep Ocean Stewardship Initiative, helping to promote and integrate ecological observations with existing and new deep-sea physical and chemical observing.
7. Collaborate with the SCOR Deep-Sea Decade working to coordinate a global effort.

V. Institutions/programmes/ networks that shall be further engaged into the preparations for and implementation of the UN Decade.

Deep Ocean Observing Strategy, Deep Ocean Stewardship Initiative, NOAA Ocean Exploration and Research, iAtlantic, Global Ocean Oxygen Network, Argo, BGC Argo, Deep Argo, GO-SHIP, OceanSITES, OOI/ONC observatories, Partnership for Observation of the Global Oceans (POGO), GOOS, CLIVAR, NASA.

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No: _____