Deep Ocean Observing Strategy (DOOS)

DOOS 2016 Workshop Proceedings

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DOOS WORKSHOP OVERVIEW
Lisa Levin, Scripps Institution of Oceanography

An international scoping workshop was held at Scripps Institution of Oceanography under the auspices of the Global Ocean Observing System (GOOS), to identify scientific and societal priorities for a new initiative, the Deep Ocean Observing Strategy (DOOS). Forty-four participants from nine countries convened from 7-9 December 2016 in La Jolla, California. Representatives were present from major global observing programs, systems, and networks such as GOOS, GO-SHIP, Argo, Deep Argo, Bio Argo, OceanSITES, Tropical Pacific Observing System 2020 (TPOS), Ocean Observatories Initiative (OOI), Ocean Networks Canada (ONC), Global Climate Observing System (GCOS) as well as international/intergovernmental organizations like Intergovernmental Oceanographic Commission (IOC), Deep Ocean Stewardship Initiative (DOSI), International Union for the Conservation of Nature (IUCN).

After an initial discussion of the GOOS Essential Ocean Variables (EOVs) (www.gooscean.org/eov) and Framework for Ocean Observing (FOO) (www.gooscean.org/foo), DOOS background, workshop objectives, and participant introductions, a series of eight presentations were given to introduce key deep-sea scientific and societal questions and issues that motivate deep observations. These encompassed climate change and the Earth’s net heat imbalance, ventilation and circulation, turbulence, biogeochemical drivers (carbon and oxygen), their ecosystem consequences, human mining and energy extraction, deep-water fish and fisheries and deep-sea biodiversity. These presentations were followed by a plenary discussion to identify the scientific questions that a deep observing system should address. The final presentations of day one covered the DOOS Consultative Draft, (Version 5 of the Consultative Draft will be used as a foundational document for the DOOS Science Guidance and Implementation Plan, see Action 14, p. 26) the Deep Ocean Observing Inventory, and a brief overview of selected national deep observing programs (one slide per nation). Scripps hosted an evening reception following the day’s deliberations.

Day Two began with short presentations and plenary discussion of EOVs for deep physical, biogeochemistry, biology and ecosystem needs. Then short overview presentations on sensors and platforms were accompanied by a more extensive plenary discussion of these topics and geographic locations to target. At lunch time the biologists began the process of re-designating their EOVs, which generally are less mature than those of the other two groups. During the afternoon breakout groups met to consider observing needs, pilot studies and integrative efforts addressing four of the main science challenges identified the previous day.
These addressed:

• The Earth’s energy and water cycle and imbalance (heat, freshwater and overturning circulation),
• Quantification of carbon uptake, flux and storage,
• Functional importance of animals and microbes at the sea floor (to inform spatial planning and impact assessment), and
• Response of the deep pelagic ecosystem to climate change and human activities.

These deliberations were then shared in plenary. There was some discussion of combining efforts for several of these programs at a single pilot location, although others did not want to see a single focal location.

The final day involved discussion of funding opportunities and data management issues. A detailed discussion was held on Terms of Reference (ToR) to identify major DOOS goals, objectives and tasks. After the conclusion of the mid-day workshop, the scientific planning committee met in the afternoon to refine and reorganize the ToR, generate action items associated with each, and outline the workshop report. Below we offer a more detailed summary of workshop presentations and deliberations.

Workshop support was provided by NASA’s Science Mission Directorate, with the reception hosted by the Scripps Institution of Oceanography Director’s Office.

**GOOS Framework and EOVs**

*Albert Fischer, IOC/GOOS*

As a GOOS Project, DOOS will be aligned with the GOOS FOO. In 2012 the GOOS adopted the FOO as a guiding document for GOOS activities and alignment. The purpose of the FOO is to deliver an integrated ocean observing system fit for many purposes. The FOO describes a clearly defined structure that allows ocean observing providers and users to participate in the system at various points. It traces a path from Inputs (requirements or EOVs) to Processes (observations), to Outputs (data and products). To maintain an ocean observing system that is fit-for-purpose, the outputs must properly address the issues that drove the original requirements. This creates a constant feedback loop such that requirements are always driven and informed by science and societal needs; and that EOVs are part of the system that responds iteratively to this evolving set of needs.

A focus on measuring EOVs provides a way for all stakeholders to speak a common language fostering collaboration in this highly voluntary system. EOVs are identified based on how feasible they are to observe and their level of scientific or societal impact. Targeting investments based on EOVs, in conjunction with the evaluation and encouragement of improved readiness levels for sustained observations, ensures a path for research and innovation to shape the evolution of GOOS.
DOOS HISTORY, DEPTH DEBATE, AND WORKSHOP OBJECTIVES
Lisa Levin, Scripps Institution of Oceanography

Mission. Although the purpose of the workshop was to scope the DOOS Actions, an initial mission statement was presented at the outset: Develop a common statement of requirements and an initial strategy for sustained global deep ocean observations; considering all EOVs, regions, technologies, and societal imperatives so as to extract high priority, feasibility, and GOOS fit-for-purpose actions for the next 10-50 years.

In translation this mission was interpreted as a mandate to:
• Develop a coordinated plan that brings together the deep observing community to address key scientific and societal needs by measuring EOVs, and
• Turn the deep ocean observing ‘strategy’ into a ‘system’.

Depth. A brief debate followed on the depths to be considered by DOOS, with the physicists arguing for “below 2000 m” and the biologists and biogeochemists suggesting that deep-sea important processes begin below 200 m. There was no final agreement, in part because the different science communities face different observational readiness and challenges. However, a reasonable compromise emerged, for DOOS to focus on the area below 2000 m with additional attention to shallower processes and mechanisms (> 200 m) that influence the deeper depths.

History. Initial DOOS discussions and DOOS Report Consultative Draft preparation began in 2010 at a preliminary deep-ocean meeting held in Pasadena, California, and proceeded episodically through 2015, when a leadership team was formed involving the Scripps Institution of Oceanography, University Corporation for Atmospheric Research (UCAR), and Consortium for Ocean Leadership (COL). In 2016, this team sought community input on the DOOS Consultative Draft, conducted a deep-ocean observing inventory, and constituted a workshop planning committee to organize this scoping workshop.
**Workshop Goals**

Initial high-level goals were to:

- Encourage increased partnerships across the deep-ocean research community.
- Align, assess and improve the readiness levels of requirements, technologies, platforms, and data products that address societal imperatives.
- Expand GOOS communities to include diverse deep-ocean stakeholders.

More specific workshop goals were to:

- Identify societal and scientific drivers for a Deep Ocean Observing Strategy – *What have we missed?*
- Define the key scientific questions that should be addressed with deep observations and what measurements are needed.
- Characterize observing systems that meet these scientific and functional requirements, and identify gaps, inefficiencies and vulnerabilities.
- Review the status of deep observing systems: platforms, sensors, and technology.
- Review and prioritize existing and potential EOVs in deep waters.
- Evaluate logistical requirements for implementation of a recommended DOOS, including: Strategies, Interest, Collaborators, Funding, etc.
- Evaluate requirements for delivery of data, and derived products and information; evaluate the existing data systems for fitness for purpose.

The hope was to leave the three-day workshop with the answer to: *What is DOOS?* To develop solid recommendations for the scope, goals, duration and structure of DOOS and DOOS leadership, a definition of DOOS projects, guidance on a roadmap for EOVs, technology, and data information product maturation, linkages to specific societal needs and organizations, and plans for OceanObs 2019.

**Action 1:** Identify and form a DOOS Steering Committee with appropriate disciplinary, programmatic, and geographic representation.
A series of presentations were given to develop the rationale for DOOS and stimulate thinking about science and societal needs. These are summarized below.

**OBSERVING AND MODELING CLIMATE CHANGE: The Deep Ocean Role**

*Greg Johnson, NOAA  
Bernadette Sloyan, CSIRO*

The ocean is a central component of Earth’s climate system, essentially carrying the climate memory from short to long temporal scales. In the context of climate variability and climate change, the global ocean plays an important role in the Earth’s heat and freshwater budgets: The ocean currently stores about 93% of the Earth’s excess heat energy (IPCC, 2015), with a considerable fraction stored beneath 2000 m depth. More than three quarters of the total exchange of water between the atmosphere and the Earth’s surface through evaporation and precipitation takes place over the ocean and cryosphere. The ocean warming has resulted in global and regional sea-level rise.

Significant changes in the temperature of the deep ocean (below 2000 m depth) in the Southern hemisphere have been observed. These changes (+0.02 to +0.05 °C/decade) are largest in the deep basins of the Southern Ocean adjacent to the formation regions of Antarctic Bottom Water (AABW). While observations of deep ocean temperature and salinity changes are determined from observation, climate models continue to show large biases in simulation of deep-ocean temperatures, on the order of hundred times that of the observed mean. Although improved model simulation of AABW can be achieved using high-resolution models, our knowledge of the formation processes and parameterization employed in models for AABW production is still not adequate to correctly simulate AABW temperature (and salinity) properties and change.

The observed deep-ocean temperature changes are determined from high-quality but sparsely distributed repeat hydrography sections (World Ocean Circulation Experiment (WOCE), Climate and Ocean: Variability, Predictability and Change (CLIVAR), GO-SHIP). The global array of these repeated hydrographic sections only observes approximately 10-15% of the ocean. Therefore, the deep ocean research community is beginning to advocate for a global array of Deep Ocean Argo floats. Significant sensor development and testing is currently being undertaken and pilot arrays of Deep Argo floats are beginning to be deployed.
VENTILATION AND CIRCULATION: Why Transient Tracers Matter
Toste Tanhua, GEOMAR Helmholtz Center for Ocean Research

Transient tracers are inert compounds with a time-specific input function or a well-defined decay function that can be used to determine ventilation time-scales in the ocean. The time-scale of ventilation is best viewed in the framework of Transient Time Distribution (TTD) as there is not a single time event but rather a spectrum of different ventilation pathways that characterize a water-mass.

Transient Tracers is an EOV within DOOS and GOOS. For the deep ocean, the tracers with a somewhat longer time-history are of particular interest. These include compounds like CFC-12 and CFC-11, but also the radioactive isotopes $^{14}$C and $^{39}$Ar that can provide information on ventilation of the deep ocean. The argon isotope is still in the concept phase due to complicated analytical requirements, but significant progress is being made on advancing that technology; the use of repeat measurements to determine temporal variability was demonstrated for the Southern Ocean and the Mediterranean Sea.

TURBULENCE
Katsuro Katsumata, JAMSTEC

Turbulence in the ocean causes mixing. Mixing mainly occurs along constant density surfaces, or isopycnals. The isopycnal mixing follows stirring by eddies at various spatiotemporal scales and is important when estimating horizontal spreading of tracers including pollutants and larvae.

Diapycnal mixing, i.e. mixing across isopycnals, plays a crucial role in closing the global overturning circulation. The energy source of the mixing is believed to be mainly the gravitational force from the Sun and Moon (i.e., tides) and the ocean surface winds. In the Southern Ocean, surface wind causes not only the mixing but also upwelling and consequent outcropping of Circumpolar Deep Water. In the energy flow from the source (Sun, Moon, wind) to ocean circulation through turbulence, the budget from the source to turbulence is closed, but the link between turbulence and ocean circulation is not satisfactory, at least in the Indian Ocean. In other words, turbulence in the deep ocean is not constrained sufficiently to close the ocean circulation, thus deep turbulence needs to be measured.

The turbulent mixing mainly occurs in centimeter scales in the vertical direction and minute to second scales in time, as kinetic energy is converted to heat through viscosity. Microstructure sensors measure velocities and temperature at these scales. But use of these sensors is still expensive and time consuming. Parameterization has been used to estimate mixing from measurements in 10-to-100 m scales in the vertical and hour-to-day time scales from CTDs (shipboard, moored or autonomous floats) and Acoustic Doppler Current Profiler (ADCPs) (lowered, moored) but requires various assumptions.
It is recommended that spatial sampling of the deep turbulence field be conducted by GO-SHIP, Argo (including Deep Argo), and other platforms (deep gliders, expendable sensors, etc.) through parameterization and that temporal sampling be concentrated in "choke points" where deep water masses are topographically steered to narrow geographic regions. The choke point stations can be combined with biological and/or biogeochemical measurements.

**TOWARDS A DEEP-OCEAN OBSERVING STRATEGY, SETTING THE STAGE: Ocean Biogeochemistry**

*Rik Wanninkhof, NOAA*

The deep ocean (below 200 m depth) plays a critical role in global biogeochemical cycles in that it contains over 90% of the labile carbon and inorganic nutrients residing in the Earth system. The canonical view that the deep ocean is in steady state no longer holds true, especially during the anthropocene with increasing atmospheric carbon dioxide levels and changes in forcing impacting the deep ocean. Roughly 80% of the anthropogenic carbon, which is 20% of the total CO$_2$ released from burning of fossil fuels to date, has already reached the deep ocean. Changes in surface water productivity, deep-water respiration and remineralization, and circulation and mixing of the deep ocean are affecting oxygen levels, as well as nutrient and carbon cycling.

Sustained monitoring of changes of inventory as an indicator of impacts, and a better process-level understanding of the controls are critical. In particular, the biogeochemical deep ocean processes are dominated by remineralization processes which are poorly understood. Both an overarching view using concepts of remineralization length scales (RLS), and thermohaline circulation, as well as process-level scales of turbulent mixing and microbial controls of remineralization and respiration are necessary to improve understanding and quantification of changes in the deep ocean.

Key issues that must be addressed include decreasing oxygen levels in the ocean, in particular the increasing size of the oxygen minimum zones (OMZ), pathways and processes of anthropogenic carbon uptake and its influence on ocean acidification, and changes in nutrients levels/dynamics in the deep ocean.

**ECOSYSTEM CONSEQUENCES OF CHANGING BIOGEOCHEMISTRY**

*Nadine Le Bris, University Pierre et Marie Curie*

Global climate models predict that deep and intermediate waters will substantially acidify and deoxygenate by the end of this century, in addition to an average 0.2 °C warming. Different combinations of these stressors will challenge ecosystem functions over the large biomes formed by abyssal plains, continental margins and mid-ocean ridges. Current observations are documenting rapid physical and chemical changes at depth and potential synergies with ecological responses, such as increase in nutrient recycling and decrease in organic carbon export through the
water column, amplifying the impacts. These interactions are not well parameterized in models, limiting the capacity to identify areas particularly vulnerable to major shifts in diversity, productivity and trophic structure, but main threats are already identified.

Surface warming is expected to reduce both oxygen solubility and ventilation of deep waters. Deoxygenation holds the potential for radical changes in deep-sea diversity and functions. Naturally oxygen-depleted waters already expanded, shoaled and deepened over large areas, setting limits for larvae and adult survival, as well as causing behavioral or physiological impairment for key species. These disturbances also impact connected shallow ecosystems (e.g., in upwelling regions or through trophic interactions) with feedbacks on the biological carbon pump. In addition, deep-water warming enhances methane hydrate dissociation and the high-biomass communities that are fuelled by methane oxidation on the seafloor will be particularly disturbed by outgassing; with still unconstrained feedback on atmospheric Greenhouse Gases (GHG) concentration.

Changes in the CO₂-carbonate system modify surface primary production and the quality and quantity of nutritional resources exported to the ocean floor. Anthropogenic CO₂ has already invaded deep waters at high latitude or in deep basins such as the Mediterranean Sea, and it is expected to impact species energetic requirements and tolerance to other stressors. Stony coral, whose occurrence is already limited in corrosive water regions of the North Pacific, will be confronted by the shoaling of the aragonite saturation horizon in large deep-sea areas, especially at high latitudes.

Long-term trends of these stressors are documented by seafloor observatories. So far, however, it remains difficult to discriminate seasonal and inter-annual variability from climate-induced disturbances. Climate change is superimposed on still poorly understood natural fluctuations of deep-sea ecosystems. Furthermore, seafloor topography hosts thousands of ecological hotspots (e.g. within submarine canyons and on seamount flanks), whose environmental conditions vary across depth, at short spatial and temporal scales ranging from centimeters to kilometers and hours to seasons. A large monitoring effort is required to understand the ability of deep-sea species and seafloor ecosystems to adapt and should cover the complex environmental mosaic spanning over ocean basins and marginal seas. There are furthermore crucial needs for observations of both environmental parameters and rates of ecological functions in habitats of high biological and ecological significance.

MINING, OIL AND GAS EXTRACTION AND CO₂ SEQUESTRATION IN THE DEEP SEA
Craig Smith, University of Hawaii, Manoa

The goals of this talk were to summarize the potential locations and ecosystem impacts in space and time of deep-sea mining, oil and gas extraction, and CO₂ sequestration, and then to highlight the major needs for sustained deep-ocean observations relevant to these impacts.
Mining. Deep-sea mining will target various mineral resources, including manganese nodules on abyssal plains, seafloor massive sulfides on mid-ocean-ridge and back-arc spreading centers, cobalt-rich crusts on seamounts, and phosphorites on ocean margins. When carried out at industrial scales:

- Industrial scale nodule mining will deleteriously impact vast, highly vulnerable seafloor areas (10’s to 100’s of thousands of square kilometers) characterized by high biodiversity through direct mining and plume effects, altering ecosystem structure, diversity, and function from decades to millennia.
- Massive sulfide mining will occur in regions with evolutionarily novel, high biomass, highly productive, charismatic vent communities, with impacts expected to extend for 10’s of kilometers and to persist for decades, or longer.
- Along-ridge biological connectivity is particularly threatened by mining activities. Cobalt-crust mining could impact whole seamounts (20 – 1200 km²), including populations of endemic species at 800–2500 m depths. Seafloor phosphorite extraction will impact shelf and slope habitats, affecting >60 km² per mining operation from direct mining and plume effects.

The impacts of mining from plume dispersal, heavy metal toxicity, altered sediment geochemistry, and larval connectivity are poorly constrained for all forms of deep-sea mining and require long-term observations of: current regimes (e.g., sediment erosion/deposition/transport); vertical Particulate Organic Carbon (POC) flux into the benthic boundary layer; particle concentrations in the Bottom Boundary Layer (BBL) and deep water column; oxygen, pH, redox chemistry in bottom waters and sediments; seafloor habitat conditions, including animal behavior, bioturbation; and benthic faunal/microbial community structure and function.

There are some relevant ocean observing platforms in the deep sea, but these are 1000s km away, and in different habitats, from current mining claims.

Oil and Gas Extraction: The marine footprint of deep-sea oil and gas exploitation is enormous, growing, and going deeper and deeper (>2000 m). Deep-sea impacts include effects from drill cuttings, drilling muds and processed water, infrastructure, and accidental spills; evaluation of these impacts requires deep-sea monitoring of parameters similar to those relevant to mining, as well as observations of petroleum markers and dispersants. DOOS will need many ocean observing systems similar to Deep-ocean Environmental Long-term Observatory System (DELOS) on the Angola Margin to monitor EOVs on margins targeted for oil/gas extraction.

Deep-ocean storage for CO₂ may include diverse strategies and locations. Deep ocean observations of key environmental and biodiversity variables will be critical for site selection and monitoring of the success and impacts of deep-ocean CO₂ storage. Because of the potentially large scale and duration of impacts from manganese nodule mining, and the poor understanding of ecosystem resilience to these impacts, it is recommended that DOOS include a series of abyssal observatories across the Clarion-Clipperton Zone (CCZ) for long-term
measurements of key ecosystem variables in the abyssal benthic boundary layer and deep water column.

**DEEP WATER FISH AND FISHERIES: ISSUES AND OPPORTUNITIES FOR DOOS**  
*Tony Koslow, Scripps Institution of Oceanography*

Two issues were covered: 1) deep-water fisheries, their sustainability and impacts; and 2) mesopelagic fishes: their role in marine food webs, potential impacts of deoxygenation, and potential as an EOV in deep ocean observing systems. Many deep-water fisheries, such as those for orange roughy, involve fishing on seamounts for long-lived taxa that have proven highly susceptible to over-fishing. While these fisheries can be highly profitable initially, they are typically short-lived and can impose severe impacts on vulnerable deep-water coral and sponge habitats. Overall they represent a small proportion of global fisheries landings.

Mesopelagic fishes represent a vital link in global marine food webs between the zooplankton and higher predators. Studies based on the California Cooperative Fisheries Investigations (CalCOFI) ichthyoplankton indicate they may be impacted by deoxygenation effects on the OMZ. Mesopelagic fishes can be well represented in standard ichthyoplankton surveys. Given the availability of such time series and the potential susceptibility of mesopelagic fishes to changing ocean conditions, in some cases through their vertical migrations, mesopelagic communities should be considered as an EOV and a source used to assess the ecological status of deep-water pelagic ecosystems.

**BIODIVERSITY IN THE DEEP SEA: THE BIO-GEOSCIENTIFIC POINT OF VIEW**  
*Hiroshi Kitazato, JAMSTEC*

Biodiversity research in the ocean is a starting point for biologists including paleobiologists. Key questions common among marine biological research studies are: What are the patterns of biodiversity in the deep sea? What are the patterns of connectivity between deep-sea ecosystems and between shallow and deep water? How do deep-sea ecosystems function and what ecosystem services do they provide?

A potential impact may be that as more research data are accumulated, the more discovery-based research may decline in favor of hypothesis driven science. One of the reasons is that some species tend to be widely distributed in the world oceans, especially among small taxa. “Everything is everywhere” can be true for some taxa in deep-sea realms. On the other hand, deep-sea ecosystems are going to be disturbed by anthropogenic activities, such as ocean acidification or deep-sea mining, especially so because deep sea ecosystems are fragile and can take long periods to recover. Thus, biodiversity researchers should focus more attention to these anthropogenic disturbances in the deep sea.

Research schemes by social technology may be applied to deep-sea biodiversity and ecosystem research for constructing overall ecosystem management as well as disaster risk management in the deep-sea. The research flow involves: (i)
observations (ii) data synthesis through databases and modeling (iii) information products such as habitat maps, (iv) delivery to stakeholders and action. Our research products should transfer to stakeholders and citizens for maintaining sustainable deep-sea ecosystems in a healthy condition. We need to construct more effective observational systems for monitoring vulnerable ecosystems in the deep sea. For this purpose, we need to develop research platforms, sensors and analytical techniques.

Continental margins are excellent target areas for monitoring biodiversity and ecosystem disturbance in the deep sea, because present human activities more directly affect the margins than abyssal plains. Natural geological hazards such as Earthquakes, tsunamis and volcanic events are common at convergent continental margins (plate subduction areas). A case study was provided on how deep-sea ecosystems can be strongly disturbed by the huge Earthquake and tsunami from the March 11, 2011 event off northeast Japan. Natural hazards sometimes provide very good natural analogues for understanding anthropogenic disturbances in the deep sea.

Four recommendations for DOOS are:
1. 4D continental margin research is needed for better understanding deep sea biodiversity and ecosystems;
2. Develop a better understanding of microbial ecosystems constructed by prokaryotes and eukaryotes as they are sometimes much more sensitive to change than macro or mega benthic communities in the deep sea;
3. We need mobile monitoring sites together with fixed monitoring sites; and
4. Multi-disciplinary research systems are needed. In particular, biologists must work with geologists and geophysicists. (The latter have already constructed useful monitoring systems such as Earthquake and tsunami early warning systems using cable networks.)

DEFINING SCIENTIFIC GOALS
Patrick Heimbach, University of Texas, Austin
Henry Ruhl, National Oceanography Centre

Major science questions
Human activities have profound, possibly irreversible impacts on ocean health, in terms of its physical state (warming, freshening, circulation changes), biogeochemistry (carbon uptake, acidification, deoxygenation), and ecosystems (loss of biodiversity, ecosystem functions and services). A major challenge persists in characterizing and quantifying these changes at depth levels that have been difficult to access via available observing systems. Day One DOOS discussions identified a set of leading research questions that are of international societal and inter-generational relevance. In most cases, adequate baseline measurements do not yet exist, and/or spatiotemporal sampling is insufficient to detect changes.

Guiding overarching science questions from which observational requirements can be derived are:
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 fresh water 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, geothermal 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 such changes influence the function of the solubility and biological carbon pumps, continental slope, nephloid 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 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 change 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, O$_2$, and POC flux. This will improve spatial planning and impact assessment for seabed mining, bottom trawling and oil and gas extraction.

The workshop identified an uneven level of maturity in deep-ocean observing capabilities between the physical, biogeochemical, and ecosystem research communities. Whereas several EOVs targeting the physical ocean state (notably hydrography) are today sampled quasi-globally down to 2000 m by the Argo profiling float program, there is a dEarth of biological and ecology observations below 200 m depth. It was widely agreed that the Deep Argo program would add considerable value in addressing some of the above questions.

At the other end of the spectrum, there is very little baseline information for the management of frontier industries like deep-water oil and gas exploitation or seafloor mining. Biogeochemical and ecological EOVs are more diverse in form and complexity (including superimposing natural variability scales) with importance in both the meso- and bathy-pelagic (down to 2000 m, where most particulate carbon is thought to be remineralised) and ultimately the bathyal and abyssal zones (below 2000 m where there is the least baseline information available, but vast seafloor areas set aside for mineral exploitation).

The discrepancy in terms of maturity calls for a multi-facetted approach, which should enable both the stringent requirements of the physical variables to be implemented, while also planning for a tightly integrated observing system meeting needs across all the disciplines.
Approaches and requirements
For each (and all) of these science foci, a basic observing system design approach can be thought of in terms of three categories:

1. Observing systems with conceptually defined (i.e., more or less known) feasible spatio-temporal sampling requirements to conduct sustained monitoring (e.g., on basin to global scale); this approach is the most readily aligned to GOOS (and GCOS) goals and implementation;
2. New pilot observing studies/programs that can eventually feed into sustained large observing system;
3. Mature systems that enable the delivery of knowledge related to human welfare.

In developing a science and implementation plan, conceptual tools can aid the observing system design. These are laid out in the FOO document. Three most relevant aspects are noted here:

• Traceability matrix: tracing observation and science requirements can map from science question to observing system specifications;
• Construction of a high-feasibility vs. high-impact matrix can help prioritization;
• Advantage should be taken of EOV requirement documents; the most detailed description here is actually in the ECVs, as laid out in the GCOS Science & Implementation Plan (2016).
• There is also a need for exploratory modeling/ OSSEs and an effort to nurture observing system elements in the concept stage.

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<th>Action 2: Distribute the list of science questions developed at the workshop and ask the Earth Science Community: Are we missing solid Earth components?</th>
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<td>Action 3: Distribute the list of science questions developed at the workshop. What needs to be added that will connect with one of the areas identified?</td>
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<td>Action 4: Distribute the list of science questions developed at the workshop. Are there necessary modifications to the European Multidisciplinary Sea-floor and water column Observatory (EMSO) questions? (See Ruhl et al. 2011, Programs In Oceanography. 91:1-33.)</td>
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CONSULTATIVE DRAFT AND INVENTORY

Andrea McCurdy, UCAR
Leslie Smith, YourOcean Consulting

In addition to the coordination and support of the DOOS Workshop, during the inaugural year of DOOS the Distributed Project Office conducted three primary activities led by the guidance of the DOOS Planning Committee (see page 5). The first activity was the community review and comment of the DOOS Consultative Draft. The review resulted in over 240 comments and suggestions from 27 different reviewers from 14 agencies and 7 countries. The themes of the comments were the need to define deep, provide geological context and content as appropriate, identify sensor and platform technology maturation at various depths, and to redraft the
The Interagency Ocean Observation Committee (IOOC) office within COL managed an online inventory for deep-ocean observing activities. Toward this end, a survey was posted on the DOOS website in August 2016 to inventory the status of sustained observations in the deep sea. An analysis was conducted using data from responses through November 2016. Specifically, the analysis looked at 70 responses from 39 organizations, representing 83 countries, and funded by 29 agencies. The goal of the analysis was to identify gaps in geographic coverage, water depth, and EOVs. Of the responses, most program-wide sampling occurred across large depth ranges (200-6000 m) 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 ADCPs. The most common mature EOVs sampled were Temperature, Salinity, Dissolved Oxygen, Carbonate System, and Primary Productivity; the EOVs most commonly suggested by respondents as key to include in DOOS were Water Velocity, Inorganic Nutrients, and Species Abundance/Diversity.

The third activity was the drafting of an online interactive map representing deep-ocean observing activities. A brief demonstration was provided, suggestions for changes and additions were offered by participants.

It was noted that all items in this discussion are available on the DOOS website: www.deepoceanobserving.org

<table>
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<tr>
<th>Action 5:</th>
<th>Add-to and complete deep ocean inventory, including mapping features</th>
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<td>Action 6:</td>
<td>Move tracers from Physics to BGC EOV category in Consult Draft</td>
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PART THREE: Technology Development & Science Focus

A series of presentations were given to develop an understanding of EOVs (requirements), technology development and stimulate thinking about geographic and science challenge gaps.

**PHYSICAL EOVs**  
*Bernadette Sloyan, CSIRO*

GOOS is organized by the user-driven requirements for EOV observations for:
• Monitoring the ocean circulation
• Monitoring the climate system;
• Detecting and attributing climate change;
• Assessing impacts of, and supporting adaptation to, climate variability and change;
• Application to national economic development;
• Research to improve understanding, modeling and prediction of the climate system.

The EOV observational requirements can be satisfied in a number of different ways using a variety of sensors and observational platforms. In order to meet the EOV requirement (spatial and temporal sampling) and to provide the greatest resilience of the observing system, the ocean observing system is coordinated through global networks which are organized around particular platforms or observing approaches (e.g. satellite constellations, Argo profiling floats, OceanSITES time series sites, etc.) and with defined missions and implementation targets. Different observing networks monitor ocean EOVs globally, but at varying temporal and spatial scales, depending on requirements and feasibility. Sustaining observations of EOVs relies on the existence of multiple platforms equipped with a range of different sensors. Having multiple independent methods for determining derived quantities is essential for a robust and resilient system.

**DOOS Physical EOVs**  
For the deep ocean the EOVs must be able to provide observations to answer the driving scientific questions. These include (but are not limited to):
• The role of the deep ocean in the Earth’s energy balance and freshwater cycle; sea level rise;
• The ocean’s ability to redistribute physical properties that are key to climate, and the magnitude of variability and change of this circulation, e.g., the (deep) global overturning circulation;
• Ocean-Atmosphere-Ice processes at high latitudes leading to deep water mass formation;
• Severe events, such as sediment transport in canyons and continental slopes to the deep ocean.

The GOOS EOVs for the physical ocean environment include: Temperature (surface and subsurface); Salinity (surface and subsurface); Currents (surface and subsurface); Sea Level; Sea State; Sea Ice (concentration, thickness, drift); Ocean Surface (Vector) Stress; and Ocean Surface Sensible and Latent Heat Fluxes. All of these existing GOOS EOVs are relevant to the deep ocean, except for Sea State.

Given the unique science drivers for the DOOS additional EOVs must be added to the GOOS EOV list. These DOOS specific EOV are:
• Ocean Turbulence
• Ocean Bottom Pressure
• Geothermal Fluxes
• Ocean Bottom Boundary Fluxes

For the Deep Ocean, we must design an observing system that encapsulates the required temporal and spatial scales for each of the relevant GOOS EOVs and additional DOOS EOVs that meet the requirement of the key deep ocean scientific questions.

**Action 7:** Update or create Physics EOV specification sheets; accuracy needs
- turbulence, bottom pressure, geothermal fluxes, bottom stress,
- add relief and topography as fundamental baseline dataset,
- add geothermal considerations.

**BIOGEOCHEMISTRY EOVs**
*Toste Tanhua, GEOMAR Helmholtz Center for Ocean Research*

EOVs are negotiated by the GOOS Biogeochemistry (BGC) Panel, based on their feasibility and impact, and are ranked based on technical readiness. The EOVs for BGC in GOOS are variables essential to answer questions about:
1. The role of ocean BCG in climate,
2. Human impacts on ocean BGC, and
3. Ocean ecosystem health.

Based on an analysis of impact and feasibility with the three points listed above as guidelines, the GOOS BGC panel compiled a list of nine EOVs. Of these, seven are listed as essential climate variables in the GCOS Implementation Plan: ([http://www.wmo.int/pages/prog/gcos/](http://www.wmo.int/pages/prog/gcos/))

The EOVs for DOOS were discussed and defined in the initial DOOS Report before the GOOS BGC panel defined the GOOS EOVs. This resulted in a few differences between the two sets of EOVs. To some extent these differences reflect the fact that due to the DOOS-specific focus on the deep ocean, some GOOS EOVs (ocean color
and nitrous oxide) are less relevant in the context of DOOS. Other discrepancies are due to differences in nomenclature and in structuring the set of EOVs, i.e., in the way EOVs are formulated / articulated and should be reconciled between GOOS and DOOS. It is suggested to adjust the DOOS science and implementation plan to be consistent with BGC EOVs, in turn to be compatible with the GOOS EOVs and their specification sheets.

**DOOS Biogeochemistry EOVs**

The plenary discussion focused mainly on:

1. Discrepancies between the BGC EOVs defined by DOOS and the GOOS BGC panel
2. Gaps in the DOOS BGC EOVs suggested so far

**Discrepancies between the DOOS and GOOS BGC EOVs**

The main differences between the two sets of BGC EOVs are:

1. Dissolved and particulate organic matter/suspended particulates are presented as one EOV by DOOS while they are considered separate EOVs by the GOOS BGC panel;
2. DOOS suggests transient tracers (e.g., CFC, SF₆, ³He, ¹⁴C) are listed as physical EOVs in GOOS;
3. N₂O and Ocean Color, being defined as GOOS BGC EOVs are not considered by DOOS.

There is agreement that discrepancies between DOOS and GOOS EOVs should be avoided where possible.

**Gaps in the DOOS BGC EOVs**

Several participants suggested including remineralization rates (in the water column and at the seafloor) as a DOOS BGC EOV due to its importance for assessing organic carbon fluxes and storage. In addition, some suggested solute fluxes, e.g., of O₂ and CO₂, at the sediment-water interface and within the benthic boundary layer as BGC EOVs. The eddy correlation method is mentioned as a promising technology to obtain these observations. Other operationally simpler and cost-effective methods may be considered depending on the benthic environment. Methane is mentioned as a possible DOOS BGC EOV, not for global monitoring but rather at key locations (such as continental slopes with methane hydrates that could release catastrophically). Other possible variables discussed were light levels as a variable relevant in the "upper" deep ocean (in line with the DOOS Consultative Draft that specifies 200 m as the upper depth limit), and turbidity throughout the full ocean. Depending on the depth layer considered, nitrous oxide may be considered also for DOOS as N₂O maxima in the meso- or even bathy-pelagic.

Some participants suggested including variables that are highly relevant for BGC observations as separate BGC EOVs even if they are defined as EOVs already by other disciplines. One example is deep ocean currents/turbulence: these observations are essential in order to assess, e.g., the fate of carbon in deep waters or benthic oxygen fluxes by means of the eddy correlation method but in principle covered by physical EOVs (DOOS: ‘Currents’ / GOOS: ‘Subsurface Currents’).
Although the EOV approach includes this as ‘Supporting Variables’ which may be defined for each EOV; some participants fear that there is a different understanding in the different disciplines, e.g., in terms of the required resolution.

There was also some discussion on whether EOVs should be restricted to the properties that are, or should be measured, e.g., in cases where several measurement approaches are used to observe the same variable (e.g., suspended particles assessed with acoustic, optical, or sample-based methods), rather address what is referred to as ‘derived variables’ in the EOV concept. For some EOVs the variable being measured and the motivation to measure it may fall into different disciplines. There seems to be an agreement that these EOVs should appear in the list of the community that requires the data. For example, if underwater sound should be observed to assess the presence of pelagic animals or the acoustic stress exposure, then it should be defined as a biology/ecology rather than a physical EOV.

**Action 8:** Specify EOV BGC unique requirements for the deep sea (e.g. accuracy)

### BIOLOGY AND ECOSYSTEM EOVs

*Patricia Miloslavich, AIMS*

This presentation explained the process developed by the GOOS Biology and Ecosystems Panel to identify biological and ecological EOVs for implementation in a sustained, global observing system. Given the complexity of marine ecosystems and the challenge of selecting key variables that may properly address their changes, the process was based on a Driver-Pressure-State-Impact-Response (DPSIR) model. This process consisted of:

- Identifying the scientific and societal needs that require sustained biological and ecological oceanographic observations,
- Evaluating the existing time series and identifying information gaps,
- Studying the impact versus feasibility of the variables being currently measured and how their monitoring would address societal needs.

Societal drivers and pressures were extracted from the mission and mandates of 24 relevant international bodies and conventions. Drivers were clustered around three areas of discussion:

- Sustainable use of natural resources, biodiversity conservation, and knowledge, Environmental quality and threat prevention and mitigation,
- Capacity building, sustainable economic growth, and ecosystem based management,
- Food security.

Major pressures identified were habitat loss, climate change, pollution (including debris and litter) and eutrophication, coastal development, invasive species, solid waste disposal, ocean acidification, extreme weather events, noise, and mining.
The feasibility, given by the current state of large-scale ocean biological observations was evaluated through an on-line survey. This survey provided information on the temporal and spatial scale of observations of different biological variables being carried out, for all marine taxonomic groups and marine ecosystems by more than 100 observing programs.

The impact of the variables was inferred through a literature search determining how many publications address each of the drivers and pressures for each of the variables in the marine environment.

Based on the above analysis, the candidate biological EOVs are: phytoplankton biomass and diversity, zooplankton biomass and diversity, fish abundance and distribution, marine turtles, birds, and mammal abundance and distribution, live coral cover, seagrass cover, macro-algal cover, and mangrove cover. The next step will be to reach a common consensus that leads to the global implementation of the proposed EOVs.

**Biology EOVs for DOOS**

Subsequent to the presentation of the GOOS Biology EOV approach, a discussion was held about the DOOS Biology EOVs presented in the DOOS Consultative Draft. Many were found to be conceptual in nature and not representative of the underlying EOV.

To address this concern a lunchtime discussion attended by most of the biologists present, led to a reassessment of potential EOVs and identifying those that are critical (i.e. primary). The list below reflects this discussion. A DOOS Biology working group will be formed to further refine these, integrate these with the Biology EOVs in the consultative draft, and develop specification sheets.

**Prospective Biological EOVs**

- Species specific density/counts (invertebrates and fish – water column and benthos)
- Size-specific body size (mass); specific biomass
- Microbial biomass (diversity/activity)
- Oxygen consumption: $O_2$ sediment profile /Sediment Community Oxygen Consumption (SCOC)
- Eddy correlation fluxes
- Bioacoustics/Biophony (animal sound)
- Anthrophony (human sound)
- Light (different wave lengths)
- Quality of organic matter C/N
- Bioturbation Pb-210
- Cold water coral coverage
- Particulate flux (labile and refractory)
- Connectivity of species (life history groupings) ($F_{ST}$)
- Cover of living habitats (e.g. chemosynthetic ecosystems such as seeps, vents, coral and sponges grounds...)

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- Bottom currents (Physics)
- Temperature (Physics)
- Nitrogen/phosphorus efflux/influx (Biogeochemistry)
- Chemical profiles of metals such as dissolved Mn (manganese) or particulate iron (Biogeochemistry)
- Eh in water
- CH$_4$ in water and sediment profile (Biogeochemistry)
- Substrate (soft/hard, composition)
- Sediment geochemistry
- Ocean sound – (frequency, amplitude – time series)
- Geophony (Earth sounds)

**Action 9:** Form a subcommittee to refine and solidify the Biology EOVs

**Action 10:** Place a BGC and Phys representation on Biology EOV subcommittee

**TECHNOLOGY DEVELOPMENT: SENSORS**

*Bruce Howe, University of Hawaii*

A necessarily brief description of the state of the art for sensors was given to motivate subsequent discussion.

**Physical and Climate:** Sensors for dynamically relevant EOVs (density, temperature, salinity (conductivity), pressure, velocity) are reasonably well developed. They include thermistors, conductivity cells, force/pressure transducers, radars, electric field, and acoustic methods. Miniaturization, power and drift reduction is needed for most. Work is underway for a new type of pressure sensor with periodic absolute in situ calibration. Large(r) scale acoustic tomography, combined with navigation and communications continues to be refined; current understanding is that its effects on marine mammals are nil. On the smaller scale, the importance of obtaining better and ubiquitous sampling of mixing and turbulence was recognized; new instruments are under development. 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 their global coverage (but lacking high temporal and spatial frequencies). In general, the pros and cons of point versus integral measurements should be considered.

**Carbon and Biogeochemistry:** Much recent progress has been made for sensors to measure carbon and BGC EOVs, e.g., oxygen, nitrate, pH, chlorophyll, suspended particles, and downwelling irradiance (from biogeochemical Argo). There is still concern about longevity and calibration stability of these sensors. Several laboratories have
concerted sensor development underway, e.g., the Ocean Technology and Engineering Group, National Oceanography Centre, UK. They have developed a family of deployable, lab quality, wet chemistry lab-on-a-chip instruments such that all share a common support infrastructure (pump, electronics, etc.) but differ in the “integrated fluidics circuit” and the reagents. Variables include: nutrients, trace metals, pH, TA, DIC, pCO2, small organics, proteins and large organics, nucleic acids, and cytometry. There is great promise here and the next five years should prove them. At the same time, continuing work is necessary to make all more robust for long-term deployment. Other small-scale autonomous sensors are becoming available and are currently being operated from floats to monitor ocean oxygen (optodes) and pH (SEAFET). They involve upgraded sensors, meeting long-term robustness and accuracy requirements.

**Biodiversity and Ecosystem Diversity:** Classes of sensors fall into imaging, both optical and acoustical, and genomics. Conventional “optical” sensors include our eye looking at organisms (e.g., microscopic observation of collections by the continuous plankton recorder) and cameras (an example was a video clip from the A Long-term Oligotrophic Habitat Assessment (ALOHA) Cabled Observatory showing a rare predator/prey event only possible with continuous power and communications). Very rapid – transformative – developments in optics, cameras, and optical imaging, as well as LED-light and batteries are underway enabling new methods (e.g., in flow cytometry). Acoustic methods are being used for imaging. “Echosounding” is extending to multibeam, broadband, short and long-range and deeper systems. Passive monitoring is developing soundscapes. Fully understanding and interpreting the data from such systems is still necessary. Use of genomics is blooming, enabled by developments in the larger life sciences enterprise. An example instrument is the Monterey Bay Aquarium Research Institute (MBARI) underwater environmental DNA sample processor. Genomics has the potential to enable measurable and quantifiable biodiversity and ecosystem diversity as EOVs. In all cases, data sets will be “big” and much effort will be required to manage and mine them.

**TECHNOLOGY DEVELOPMENT: PLATFORMS**

*Uwe Send, Scripps Institution of Oceanography*

A range of platforms were presented which lend themselves to carrying sensors for deep observations; here loosely taken to be those below about 1000 m. A focus was given to those which can be used in a globally distributed fashion, which includes research vessels, moorings, open-ocean and deep gliders, deep Argo floats, ice-tethered profilers, acoustically tracked SOund Fixing And Ranging (RAFOS) floats, sensors on subsea cables, bottom landers and benthic ecological observatories. (In more specific regions, cabled observatories and deep-diving mammals can also be instrumented, and deep AUVs are under development.)

A possible approach for DOOS is to assemble a platform inventory (existing and planned) from the GOOS Panels and identify which of those can be exploited to address high-level science questions, meet societal needs, identify geographic gaps, to compare time/space coverage and accuracies, to identify gaps which DOOS can advocate for, and to exploit technical/analytical capabilities, e.g., floats/gliders sample more locations but fewer variables; moorings can carry more advanced sensors and be calibrated before/after; ships can take full suites of water samples.
In the near-term, advances can quickly be made by adding BGC and ecosystem sensors in the deep on some existing OceanSITES moorings (“proven sensors” in operational mode, “pilot mode” for more advanced/innovative sensors) and to build a small number of Deep Argo floats with BGC and ecosystem sensors to be deployed in both pilot projects and mature arrays. These platforms can thus be used to identify deep ecosystem regimes, hotspots, mining areas, or choke points where additional deployments of infrastructure are of scientific value across disciplines, and address a societal need. This discussion can be guided or framed by consideration of the EOVs needed for the high-level science objectives and by the maturity level of sensors (for telemetry needs, data bandwidth and on-board pre-processing power is also a consideration). Additionally, areas requiring environmental impact assessments (e.g. extraction or disposal sites) or ecological quality monitoring (including vulnerable habitats in Marine Protected Areas (MPAs) may serve as distributed field stations where repeated monitoring will be performed and could be completed with a suite of EOV sensors.

In the longer term, trans-oceanic submarine telecommunication cables can deliver modest power and communication to nodes every ~100 km, providing long-duration high frequency sampling over a significant fraction of the ocean (footnote: Joint Task Force (JTF) SMART Cables Initiative, http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx). Initial planning calls for temperature, pressure and acceleration to be monitored; subsequent sensors could be added as the technology develops further.

Following OceanObs’19, DOOS could make progress 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.

**GEOGRAPHIC LOCATIONS**

*Matthias Lankhorst, Scripps Institution of Oceanography*

The session about the aspect of geographic locations in the DOOS requirements emphasized that it is not only to define what needs to be observed, but also where to observe it in space. Intrinsically linked to the spatial resolution is the temporal resolution of the measurements, because having high resolution in one dimension tends to leave fewer resources to cover the other. Prioritizing different geographic locations needs to be based on the overarching science questions.

During this session, the following science topics and questions were discussed:

- Constraining Earth’s energy imbalance and net fresh water fluxes;
- Understanding the global overturning circulation;
- Constraining Earth’s carbon cycle;
- Understanding and quantifying the role of geo-fluxes across the seafloor;
- Improving timeliness of warnings for geohazards;
- Ecosystem functioning in the deep sea and on the seafloor, including their relation to environmental conditions;
- Ecosystem changes in the deep ocean due to human activities.
Regarding the first two items, heat and water storage as well as global circulation, we see the need for continued observations from satellites (altimetry, gravimetry) and in-situ systems. Deep Argo floats, moorings, seafloor pressure sensors, and acoustic thermometry and tomography, combined with float navigation were mentioned, and key to success is the combination of multiple data sources. Gaps in the present knowledge of these two science topics exist with respect to turbulence and narrow boundary currents.

Boundary currents define geographic locations where DOOS might prioritize. For observations of turbulence by floats and ships, the Pacific and Indian oceans at large were mentioned as primary areas of interest, since these are presumed to be the places where the global overturning is mediated by turbulence. The deployment strategy for Deep Argo, as for any Lagrangian program, should strive to re-populate coverage gaps as they appear. A discussion of circulation choke points, particular currents, or basin-wide measurements did not result in specific recommendations regarding priority locations. Measurements in the deep ocean require particularly thorough calibration and data quality control, because the signals of interest might be small and prone to measurement errors, both random and systematic.

For the carbon cycle, geographic locations of priority were called out as the locations of deep water-mass formation, as well as some sort of distributed global coverage, such that each large marine ecosystem would be covered by at least one observatory. Distinguishing between natural and anthropogenic signals is important and drives interest in different locations. A present gap in observations seems to be slope regions along the continental margins where deep corals exist.

Regarding geophysical fluxes across the seafloor, geographic locations of interest are the mid-ocean ridges, continental slopes and margins, and volcanic arcs. The role of these fluxes from below in relation to inputs from above generally needs better qualitative and quantitative understanding. Fluxes of interest include those of nutrients, iron, methane, and heat. The role of the abyssal plains is perhaps even less well known due in part to smaller fluxes that accumulate over large areas.

Geohazards that were discussed include tsunamis due to earthquakes at the known convergent margins, but also due to unstable sediment deposits and methane hydrates on continental slopes. Anthropogenic hazards include those caused by mining and oil and gas extraction. The geographic locations of both the continental slopes and human activities are well defined, but the discussion showed some uncertainty whether these topics should be included under the DOOS umbrella.

The final two science topics focused on deep-ocean ecosystems. Again, deep-sea mining and oil/gas extraction sites stood out as regions where observations are needed, both to determine a baseline before human impact and to document possible anthropogenic changes. For mining, the CCZ in the East Pacific seems relevant.
Apart from the locations with known human impacts, geographic focus should perhaps be distributed such that each large marine ecosystem province is covered by some form of observation. There are classifications of deep ecosystems under development, which may serve to guide these efforts. As far as biodiversity and ecosystem services are concerned, attention should be paid to marginal seas that concentrate multiple human impacts and are often lacking a coherent observing system for climate change (even for physical EOVs), making prediction of cumulative stresses impossible. The potential for rapid changes in small ocean basins are as important as large biomes of global relevance.

### Action 11: Identify gaps (knowledge, geographic, variables, technical) and emerging systems relative to the key science and societal questions

### Action 12: Synthesize workshop notes on identified observing requirements and gaps (research, geographic? other?)

### SCIENCE QUESTION BREAKOUT DISCUSSIONS

Based on the list of science questions generated on Day One, four groups were formed to discuss how DOOS might address these. Several questions were combined (e.g. regarding heat, freshwater inputs and overturning circulation) and some were not addressed (those related to geological sciences) due to limited expertise present. Below are summaries of the group deliberations.

### BREAKOUT SUMMARY: ENERGY IMBALANCE AND OVERTURNING CIRCULATION

*Lyne Talley, Scripps Institution of Oceanography*

**Rationale:** Large-scale ocean circulation plays a key role in the transport of heat from the tropics to high latitudes and from the surface to the deep ocean, heavily influencing global climate. There are gaps, however, in our knowledge of detailed aspects of the global overturning circulation and its variability. Specific to the deep sea are deep and bottom water formation rates and water properties, circulation and deep-ocean mixing, geothermal fluxes, and the impact of these on the deep ecosystem.

As scientists seek to solidify key aspects of these complex systems, they must do so in the context of how the processes may change in a warming world with a changing hydrological cycle, as both warming and salinity changes affect ocean stratification and hence strength of the overturning circulation. In terms of the Earth’s energy imbalance and land-sea water redistribution, the deep ocean is most strongly affected in the high latitudes (Southern Ocean, subpolar North Atlantic). As such an additional focus needs to be made on observations in these areas.

The largest contributions to globally averaged sea level rise are thermal expansion and increased melting of land-based ice. Geodetic changes due to slow rebound of the Earth from the last ice age and melting ice sheets also contribute. While upper ocean warming dominates thermal expansion, 10 to 20% of the warming is in the
deep ocean, most of it in the Southern Ocean, but it has not been mapped or observed in detail other than through decadal hydrographic surveys.

**How, what and where:** Observing systems for the global overturning circulation are in place at specific latitudes in the Atlantic Ocean, focused on observing variability in transport and properties of the North Atlantic Deep Water overturn, with components reaching into the AABW. The Atlantic observing systems are resource-intensive, including moorings, cables, volunteer observing ships, and interannually-repeated hydrography, along with distributed satellite and core Argo (0-2000 m) observations. Long-term but less continuous observations have also been made in the Drake Passage of the Southern Ocean, which is a circulation ‘chokepoint’. Because of complex topography and basin size/geometry, what works in the Atlantic will not work in the other oceans with the exception of narrow constrictions. Changes in the Pacific, Indian and Southern Ocean deep overturning circulations and deep properties are currently monitored only through decadal hydrographic sections with few direct velocity measurements. As a measure that can be implemented quickly, OceanSITES has assembled an instrument pool of temperature-salinity instruments that can be deployed on existing sites.

The principal approaches to observing overturning circulation for the deep Indian and Pacific include: (1) broad-scale deep Argo float temperature/salinity profiling to observe variability in deep properties and circulation throughout the deep basins, including the Atlantic to bind together the local observing systems; (2) decadal repeat hydrography (GO-SHIP) as is already used for snapshots of the circulation and properties; and (3) focused regional observing systems in a limited number of the Deep Western Boundary Currents (DWBCs) that move bottom and deep waters meridionally, and in constrictions such as Drake Passage. Improved observations of global sea level changes and barotropic flow would benefit from (4) carefully selected bottom pressure measurements with improved long-term sensor stability.

1. Central to nearly continuous deep ocean observations in the near future is the internationally agreed upon straw plan for Deep Argo: 5 x 5-degree distribution, sampling between 75-90% of the deep ocean, nominally every 15 days. Deep Argo is in pilot phase now and is poised to expand globally, subject to acquisition of sustained funding.

2. GO-SHIP hydrographic surveys provide decadal snapshots of properties and circulation, with highly accurate measurements. They have been effective in quantifying changes in ocean heat, freshwater (salinity), and carbon, as well as nutrients and oxygen. But their temporal and spatial coverage is very sparse. They must remain part of the evolving global observing program, even as it evolves to global deep Argo, because they provide the reference standards for accuracy. They also provide excellent platforms for novel measurements, including BCG and biology.

3. DWBCs are too narrow to be resolved by deep Argo. Passage circulations, such as the Antarctic Circumpolar Current through Drake Passage, are difficult to monitor with floats because of rapid circulation. Some DWBCs have already had
significant but not continuous observations using moorings. For example, the Samoa Passage in the South Pacific, through which bottom waters flow northward into the abyssal tropical and North Pacific, has been instrumented at different times over the past decades, and would be an appropriate location for a pilot experiment using modern technology. New technology approaches could include deep (super) gliders and modern moored instrumentation, including bottom pressure and inverted echo sounder measurements.

By focusing on a few small-scale areas in key locations around the globe to conduct pilots, it will be possible to examine several aspects of the system in an interdisciplinary study. A limited number of locations would allow for the examination of ecosystem connectivity, establishing how larvae drift through these locations as well as the transport of biogeochemical properties. A study, including model sensitivity, should be undertaken to identify the most important DWBC regions to observe. The southwest Pacific, including Samoa Passage, is a potential candidate, and has already been extensively surveyed with moorings and GO-SHIP sections. Efficiencies might also be found by pairing new DWBC observatories with co-located upper ocean western boundary currents, for instance in the Agulhas in the Indian Ocean.

Similarly, more observations are needed in the Antarctic Circumpolar Current, specifically continuing and improving Drake Passage transport monitoring. Additionally, bottom water formation along the Antarctic shelf, at the many documented polynya formation sites, needs to be observed and quantified. A pilot study in the Australian-Antarctic basin is suggested. Though monitoring transport from shelf cascades is difficult, deep Ninja's (www.jamstec.go.jp/ARGO/deepninja) could be utilized on the slope with deep Argo floats in the nearby deep basins to see the downstream storage change. The Antarctic shelf would also be a particularly interesting area to sample under permanent ice to examine freshwater changes.

4. A new deep ocean observing system for sea level, separating steric from mass change, is possible and important. This work requires altimetry and Gravity Recovery and Climate Experiment (GRACE) satellites as well as in-situ bottom pressure sensors to calibrate GRACE, in addition to Deep Argo. Overall the calibration method is very stable and accurate in low noise regions. Before a broad scale effort can take place, however, the accuracy of the technology needs to be rigorously examined, for example, the drift issue for bottom pressure sensors (in this regard, there are technology developments and demonstrations in progress now). SMART cables with bottom pressure sensors would be a useful addition in this case. Key locations for this work include the equatorial Pacific at tropical moored array sites, the Southern Ocean for geodesy, as well as others deemed necessary by the community. Acoustic tomography remains a potentially under-explored means for accurate monitoring of (deep) ocean heat content changes.

It was also discussed that OceanSITES is in the process of selecting sites and launching deployments, preferably at locations that provide global coverage, at
depths in the bottom layers and optionally in the deep water column above, and preferably at locations near GO-SHIP lines to provide context.

**BREAKOUT SUMMARY: CARBON CYCLING**

Contributors: H. Ruhl (Rapporteur), Felix Janssen, Orest Kawka, Nick Rome, Uwe Send, Toste Tanhua, Rik Wanninkhof

**Rationale:** Deep ocean carbon uptake and storage was a key theme that was raised in several ways during the science objectives discussion. This theme frames the scientific need for constraining Earth’s carbon cycle through quantifying deep ocean carbon uptake and storage through time, their impacts thereof on ocean acidification, changes in the biological pump, and the sequestering of carbon in the deep ocean. Discussions focused on three facets including 1) carbon inventory observations in the deep ocean 2) observations of biological pump variation throughout the water column and related carbon remineralisation / sequestration, and 3) improving high-frequency EOV observations from fixed point reference stations at the known surface forcing locations (i.e. water mass formation/carbon sequestration sites).

**How:** The inventory of dissolved inorganic carbon and its constituent chemical species warrants increased attention including work to understand the natural variation over time, as well as the anthropogenic climate change signal. The small changes in overall inventories over time require special attention for accuracy. EOVs here include pH, CO₂, carbonate, ¹⁴C, along with essential supporting variables like O₂ and nitrate. In situ lab-on-chip and wet chemical reference capability is also emerging, which enables high quality measurements with considerable accuracy to be taken from autonomous systems. Measurements with no post deployment calibration pose objectionable challenges for achieving climate-relevant accuracy. This challenge is now partly overcome by the ability of these lab-on-chip systems to carry laboratory reference standards on sensors that can be mounted to several types of platforms including deep Argo. Until these are mature, moorings are recommended which can carry multiple sensors for cross-validation, with wet chemical references, and which can be post-calibrated after recovery. Go-SHIP still provides the gold standard occasional reference data. In the long term, a larger subset of these observations is expected to be feasible from Deep Argo.

**What:** Biological carbon pump (BCP) terms like particulate inorganic and organic carbon (PIC and POC) flux and respiration/remineralization come from a small number of sites globally. Deep moored sediment traps are highlighting the highly variable nature of vertical carbon transport and sequestration terms, where pulses over days to weeks can deliver quantities influencing longer-term averages. However, high quality measurements of BCP terms like the C export ratio and the particulate C RLS are currently only made over the scale of individual research cruises. This is because the specialized free drifting traps needed to collect samples require vessels support. We recommend improving the use of moored systems to collect BCP EOVs including deep CO₂ or pH plus DIC or alkalinity, O₂, nitrate, and deep POC and PIC flux – together these will allow continuous estimates of deep biological processes. The diversity of EOVs collected could be improved with optical
systems mounted on autonomous platforms and collecting optical backscatter size and type specific particle distributions over time. Repeated benthic SCOC measures by means of microprofilers and benthic chambers attached to stationary or moving benthic platforms (landers, crawlers) allow to assess rates of organic matter remineralization and their variability and have highlighted major inequalities between benthic food demand and trap-based quantifications of food supply and thus questions about pelagic-benthic coupling and carbon cycle variation in the deep ocean. Benthic time-lapse photography adds valuable context on spatiotemporal patterns of organic matter supply directly at the seafloor and can be extended to imaging of fluorescence or absorption spectra to estimate chloroplastic pigment concentration as a proxy for food quality/lability. Image-based assessments should be accompanied by repeated measurements of organic matter quantity and quality by analyses of sediment samples for chloroplastic pigments and other biogenic compounds. BioArgo is a valuable contributor to this, however only adds optical backscatter and chl-a sensing, partly because the volumes of high resolution images needed to image larger particles and plankton are not readily transmitted by satellite. Long-range autonomous underwater vehicles (AUVs), however, offer a novel platform on which to mount optical systems that can collect and store large volumes of image data until recovery.

For determining the surface input of carbon and oxygen into the deep ocean in the source regions, high-frequency moored observations of gas fluxes and physical and biological pump are needed in the known water mass formation regions. This is crucial to resolve both the deep mixing events and blooms which occur on short timescales in limited geographical regions, and the control they have on the sequestration and inventory sources.

**Where:** Generally speaking, multi- and inter-disciplinary site research ranked highly in the discussion because such places would be natural focal points, where major biogeochemical provinces could be occupied by such efforts. Of particular note are high latitude water mass formation areas (e.g. Labrador Sea and Southern Ocean). Many deep biogeo graphical regimes are well covered by the sites proposed by the SURFACE global ocean acidification observing network (GOA-ON). The GOA-ON stations map could serve as a starting point for considering where to add deep carbon and biogeochemical cycling efforts to sites. Some notable sites of biogeochemical research at deep depths include Station ALOHA with the Hawaii Ocean Time Series (HOT) and the ALOHA Cabled Observatory, Bermuda Atlantic Time-series Study (BATS), central Labrador Sea, Porcupine Abyssal Plain, Sta. M, Frontiers in Arctic Marine Monitoring (FRAM), North and South Oligotrophic Gyre (NOC and SOG), and Cape Verde Ocean Observatory (CVOO), OceanSITES, Go-Ship, European Multidisciplinary Seafloor and water column Observatory (EMSO), OOI, and ONC. Efforts at each of these sites offer considerable organization and infrastructure leverage and coordination among them towards carbon cycle research goals is recommended. Many of them can act as platforms of opportunity to deploy deep biogeochemical sensors. Geoengineering pilot sites will also benefit from detailed carbon inventory research.
BREAKOUT SUMMARY: DEEP PELAGIC ECOSYSTEM RESPONSES TO CLIMATE CHANGE, DEOXYGENATION, ACIDIFICATION AND HUMAN ACTIVITIES

Contributors: H. Davies (Rapporteur), J. Barry, J. Koslow, K. Gjerde (Discussion Leader), S. Baumann-Pickering

Rationale: Deep pelagic (DP) ecosystems are of critical societal importance, providing ecosystem services and goods such as fisheries. There is a need to establish the current status (i.e., community structure) of deep pelagic ecosystems and to understand their variability over time, responses to environmental variability, climate-change (deoxygenation, acidification, warming), and human activities (e.g., fishing, sea-bed mining, deep-sea tailing placements, ocean fertilisation and related C sequestration efforts). Moreover, understanding the consequences of community changes (e.g. increasing microbial dominance or food web disruption) for the function and flow of energy through the deep pelagic ecosystem is important in characterizing its role in the global ocean carbon cycle.

A deep pelagic DOOS program could investigate questions such as:

- Is deoxygenation occurring globally and how fast?
- How quickly are deep ocean carbonate parameters changing?
- Is the structure of mid-water pelagic communities changing globally?
- How do local to regional anthropogenic activities (e.g. mining) affect deep pelagic communities?
- Is the flux of organic C toward the seabed changing due to shifts in the composition or function of the deep pelagic ecosystem?

What: A systematic characterization of deep pelagic ecosystems requires measurement of several aspects of biological components (i.e., abundance, biomass and size of key taxa - from microbes to megafauna - throughout the food web) and important environmental parameters (e.g. temperature, salinity, dissolved oxygen, carbonate system parameters [pH, TA], currents/turbulence, sinking POC flux). DOOS measurements could be acquired using various platforms and methods. Argo floats (core, deep, bio) can provide key variability to document environmental parameters. Acoustic methods (e.g. multi-spectral active acoustics targeting various taxa such as pteropods, cephalopods, etc., or passive acoustic documenting soniferous species and anthropogenic activities) and can contribute to visual sampling (e.g., remotely operated underwater vehicle (ROV)& AUV video surveys, profiling camera system, optical plankton counters) can characterize faunal communities. Advances in machine learning to automate the identification and quantification of organisms in image or acoustic data sets may play a critical role in DOOS (and other survey efforts). Fish egg and larvae surveys using optical or traditional (net) samples could be important in characterizing adult populations of poorly sampled taxa. POM and POC fluxes (sediment traps, particles counters) will be an important measure linking surface and seafloor environments with the DP. Emerging methods such as eDNA and genomics, along with machine learning hold great promise for simplifying the characterization of ecosystem structure, but remain unproven. Acoustic tracking of tagged animals around sentinel stations
equipped with hydrophone arrays may help resolve the effects of deoxygenation on the foraging ranges and related environmental limit of key predators near OMZs.

**Where:** A deep-pelagic DOOS program could be divided into key sub-programs (e.g. sediment trap and sample collection; optical; acoustic, genetic) and would benefit from strong ties to related or parallel studies in the upper water column and seabed. Existing (e.g. continuous plankton recorder; Hawaii Ocean Time-Series (HOT), CalCOFI) and new (e.g. NE Atlantic, NW Pacific and Poles) time-series observations would establish baselines and enable comparisons between regions to understand ecosystem responses to change. Establishing baselines and observing areas adjacent to mining activity (e.g. the CCZ), could allow detection of ecosystem changes caused by mining. DOOS could also propose monitoring programs to detect change over time in areas subject to mining activity. DOOS could provide a framework for cross-disciplinary discussions, international science coordination and cooperation with private sector (e.g. International Seabed Authority (ISA) contractors). A DOOS deep pelagic program could draw on physical and biogeochemical measurements from outside the DOOS context (e.g. Argo) and be complemented by lab studies to investigate the sensitivities of organisms to environmental change.

**BREAKOUT SUMMARY: FUNCTIONAL IMPORTANCE OF ANIMALS AND MICROBES IN THE DEEP OCEAN**

**Contributors:** P. Snelgrove (Rapporteur), K. Yarincik, P. Miloslavich, S. Muslow, K. Oguri, F. De Leo, B. Kirkpatrick, C. Smith, A. Soule, L. Levin, K. Hardy; N. Le Bris

**Rationale:** The deep sea floor covers more of the Earth’s surface than all other habitats combined. Despite generally lower abundances and smaller sizes of organisms in the deep sea, the vast area of the environment results in significant functional contributions from living organisms critical for life on Earth. Researchers have recognized that living organisms in that environment, from microbes to fishes, play a major role in the delivery of diverse functions, including nutrient recycling, carbon remineralization, habitat provisioning, trophic support, buffering greenhouse gases, biomass production, provisioning of genetic resources, and carbon sequestration. Although the link between biodiversity and delivery of these functions remains tenuous, the few studies that have addressed the question in the deep sea suggest that functional groups linked to feeding may be effective predictors of spatial and temporal variation.

Although humans have impacted the deep sea less than most habitats on Earth, impacts have occurred through benthic trawling (e.g., many seamounts and continental slopes), oil and gas extraction (e.g., continental slopes of Gulf of Mexico, Brazil and Angola), and exploratory stages of deep sea mining (e.g., Clarion-Clipperton Zone, Papua New Guinea hydrothermal vents). Climate change impacts are projected for the deep sea through alteration of food supply from surface waters, but also through changes in water temperature of sinking water masses (e.g., Labrador Sea, Southern Ocean). Below we address the why, what, where, how and when of evaluating deep-sea functioning.
**Why:** In light of these pressures and critical functions of deep-sea habitats, how can we identify the functional importance of animals and microbes in the deep sea and the seafloor? What environmental conditions (e.g. water velocity/benthic storms, turbidity, T, pH, O2, POC flux) do they experience, how do those conditions vary in space and time, and how does this variation influence biodiversity and function? Such knowledge would inform spatial planning and impact assessment for seabed mining, bottom trawling and oil and gas extraction, and help in understanding the functioning of the largest and most pristine habitat on Earth.

**What:** The remoteness of most deep-sea environments pose challenges to repeated measurements in space and time necessary to infer meaningful understanding of these functions, how they vary, and how they link to biodiversity. To address such questions requires a series of transportable arrays, (i.e. a DOOS Benthic Mobile Observatory Array) that includes moorings and landers that can be deployed at sites that address fundamental scientific questions and can be re-tasked based on evolving scientific interests. Ideally such a strategy would utilize existing infrastructure to create a standardized series of measurements to address key benthic ecosystem questions. These could include ongoing observatory programs such as the NorthEast Pacific Time-Series Undersea Networked Experiments (NEPTUNE) (continental slope), Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) (continental slope), ALOHA Cabled Observatory (oligotrophic abyss) and locations of repeated scientific missions (e.g. CCZ abyssal plain), Mid-Atlantic Ridge, Mediterranean (climate change hotspot), and Mexico, Chile, Equatorial Eastern Pacific, Indian Ocean and Peru (OMZs).

**Where:** As noted above, we must capitalize on existing opportunities but also prioritize geographic selection based on critical scientific questions and spanning geographic locations expected to be hotspots for specific functions. Thus, for nutrient cycling hotspots, target locations might include upwelling regions, abyssal plains (large area), canyons and seamounts, representative deep-sea habitats of biological significance (EBSAs), and productivity end-members. These studies might require a gap analysis in some instances (e.g. roles of microbes).

**How:** Such a program would require enhancing connections between existing deep ocean observatories, but also achieving sustained and inter-comparable measurements at new locations including the possibility to expand them with arrays of small-scale observatory systems associated with areas of specific importance (e.g. sites of cumulative human impacts, deep-water formation, cold water coral and other key habitats). Adding sensors at existing observatories will not be sufficient. This might include negotiating whether any of the OceanSITES moorings could be moved; if not, then locations near OceanSITES moorings could be considered in order to integrate water column and seafloor measurements as effectively as possible. SMART cables could enhance connections between existing or newly developed ocean observatories.

**When:** Although the scientific community recognizes the urgency for better understanding of functions in the deep ocean; prioritizing locations and the feasibility along with the need for specific measurements will require further
consultation. Thus, the more urgent need for this theme is to convene a workshop with international experts to define the where and what of biological function measurements.

**Action 13:** Identify task teams and working groups to address specific gaps

**Action 14:** Write outline and timeline for drafting the community DOOS Science Guidance and Implementation Plan

**Action 15:** Conduct or identify events to connect with stakeholders from various fields (industry, intergovernmental)

**Action 16:** Work with OceanITES to assist in the identification of locations that provide global coverage

**Action 17:** Develop ways to promote existing opportunities among communities

**Action 18:** Generate one-page write up by the Carbon group, benthic functional group, and the deep pelagic group and consider how they could integrate proposed research

**Action 19:** Create maps by decade of coverage of the EOVs across all disciplines – to underscore the vacuum of observations, updated on 2-year basis, taking advantage of existing infrastructure and data systems. (Use JCOMMOPS as a resource.)

**Action 20:** Document and post best practices of existing networks (observation techniques, data management) for deep observing, compile and coordinate relevant distribution activities

**Action 21:** Formulate a technology roadmap from the deep observing requirements

**Action 22:** Have the steering committee address tech transfer and tech capacity building
PART FOUR: DATA MANAGEMENT, TERMS OF REFERENCE, PARTICIPANT AND STAKEHOLDER ENGAGEMENT, PILOT SITE PROPOSAL

A series of presentations were given to address DOOS data management needs, to further scope the project through an agreed to ToR, to assess stakeholder and participant engagement going forward, and to discuss the concept of a potential, initial pilot site that will address multinational and multidisciplinary needs for deep ocean observing.

DATA MANAGEMENT SUMMARY

Ward Appeltans, IOC, UNESCO
Karen Stocks, Scripps Institution of Oceanography

The responses collected via the DOOS survey brought some insights into data management aspects of the 41 monitoring programmes or projects that responded at the time of this analysis. Almost all (98%) their data are archived in national data centre repositories, and 90% reported their data are accessible online, of which 60% are immediately open access and the rest mostly after an embargo period. Ninety-three percent of respondents have an established data quality control process. When asked what type of collaboration was most desired 40% responded that data sharing was of most interest. The presentation provided an overview of two existing GOOS/IOC activities of relevance to DOOS.

The concept for the GOOS Strategic Mapping Database was introduced. This will become the database model of what GOOS is. It will document the status of the observing systems in terms of which EOVs are measured by whom, where, how and for what purpose through linking the EOV measurements to phenomena or processes and scientific questions, which in turn are linked to societal benefit areas. The database will also document which tools, best practices, protocols and data systems are used including links to the products derived from these measurements. The GOOS database is still in concept phase, planned development is in early 2017.

The Ocean Biogeographic Information System (OBIS) is a global data system for marine species distribution data. It runs under UNESCO-IOC since its adoption in 2009 as a legacy from the Census of Marine Life. It integrates millions of occurrences from over 2000 databases provided by 600 institutions and a network of 27 OBIS nodes. The OBIS network is engaged in capacity development (training), science synthesis and models, ocean governance and assessment. The recently established deep-sea OBIS node in collaboration with the International Network for Scientific Investigations of Deep-Sea Ecosystems (INDEEP), aims to better engage the deep-sea biodiversity community with OBIS and improve the data coverage of the deep sea. Currently, from all the stations (data aggregated by 0.1 degree grids
and depth) that have more than 5 years of data, only 1% is deeper than 200m (393 vs 26,196 grid cells) and none are below 4000 m. Important new developments involve the expansion of OBIS functionality beyond the DarwinCore Occurrence Core, embracing Event Core measurements and sampling methodology of the OBIS standard, allowing OBIS to capture and leverage more metadata and data from collection events. This will put OBIS more in line with the broader global move toward observations and measurement data systems and better serve the needs of GOOS, DOOS, and Group on Earth Observations Biodiversity Observation Network (GEO BON).

The DOOS consultative draft provides a framework for considering a data management component for DOOS. First, it clarifies the scope: “data” management includes the management of all relevant digital products (and the term information management is used synonymously). This may include observed or raw data, processed data products, model output, the models themselves, and other software tools, code, documentation, etc.

Second, it proposes that defining a data system architecture is premature at this point in DOOS organization, with major DOOS activities and priorities still being defined, but that some guidelines can be established. First, DOOS should promote open data and best practices for information management in the DOOS community. Second, any DOOS information system should be aware of and leverage the substantial existing information management infrastructures worldwide that already hold DOOS-relevant data. Creating a stand-alone DOOS data system that duplicates existing data or services is neither sustainable nor efficient. Finally, the DOOS information management approach should be driven by the requirements and priorities of the DOOS science.

In developing a DOOS information management plan, critical questions to ask are:

- What data/products/tools are needed to address the DOOS science priorities?
- What data/products/tools are needed to communicate the science outcomes to target communities?
- To what degree will DOOS science rely on data created within the DOOS community, vs. data created by communities that are clearly external to DOOS (e.g. satellite data, commercial fish landings)?

The creation of a Data Management Subcommittee was proposed as a next step in the DOOS information management planning.

<table>
<thead>
<tr>
<th>Action 23: Create a Data Team</th>
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<tbody>
<tr>
<td>Action 24: Conduct a deep ocean data audit (Are delayed-mode data systems capturing data? Audit by country, program, identify contributions to the global challenge, from the major aggregators, track evolution over time. Audit for protocols and standards, QC, connection to aggregators, repositories)</td>
</tr>
</tbody>
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**TERMS OF REFERENCE**

*Lisa Levin, Scripps Institution of Oceanography*

*Andrea McCurdy, UCAR*

*(Draft 16/12/16)*

**Objectives:**
The purpose of the Deep Ocean Observing Strategy (DOOS) is to improve understanding of the state of the deep ocean (>200 m) with respect to baseline conditions, response to climate variability and response to human disturbance. DOOS will identify approaches to address key scientific questions and societal needs, design and evaluate appropriate observing systems, pilot projects and process studies. The evaluation of observing systems and data will follow the accepted principles outlined in the FOO and GCOS monitoring principles.

**Terms of Reference:**

1. **Build understanding on what is most important to observe:**
   a) Identify important science and societal questions and relevant variables for stakeholders.
   b) Identify the high priority processes and phenomena in the deep ocean to observe.

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

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

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

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

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

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

ROUND TABLE OF PRIORITY ITEMS

Kruti Desai, Consortium for Ocean Leadership
Nick Rome, Consortium for Ocean Leadership

At the end of the meeting all participants were asked to offer their hopes and primary goals for DOOS (for a complete list see Appendix 4). There was general agreement that the time is right for an international deep-ocean focused observing program. Key recommendations to emerge were that DOOS:

- Clarify its mission
- Engage in capacity building and advocacy (extending to the broader deep-ocean community)
- Develop inputs from solid Earth and other communities
- Build on existing infrastructure
- Organize future focused workshops
- Expand EOVs
- Write a detailed Implementation Plan
- Explore the concept of deep-ocean “supersites” for pilot projects
- Conduct an audit of deep ocean data sets

STAKEHOLDERS

Kristina Gjerde, International Center for the Conservation of Nature

Ocean observing is essential to achieving United Nations Sustainable Development Goals and other international legal commitments including the UN Convention on the Law of the Sea and the Paris Agreement. These commitments include globally agreed goals, objectives and targets for sustainable development, the conservation and use of marine resources and the protection of the marine environment. Coordinated long-term deep-sea observations can provide scientific knowledge that is key to informing decision makers, the evaluation of environmental impact assessments, the effectiveness of environmental mitigation and other management measures, and the design and monitoring of area-based management tools including
MPAs. Ocean observing is therefore a crucial tool for UN agencies, States and other actors involved in implementing such obligations. For example:

• The United Nations Sustainable Development Goal 14 (SDG-14), Oceans and Seas, elaborates a number of international priorities which must be informed by ocean observing systems, including: the impacts of ocean acidification, implementing science-based management plans for fisheries, conserving 10% of marine and coastal areas by 2020, increase scientific knowledge to improve ocean health and enhance the contribution of biodiversity to developing countries.

• The International Seabed Authority (ISA) is charged with managing seabed mining in the international sea-bed area beyond the limits of national jurisdiction on behalf of all humankind. Long term ocean observing is needed to develop baseline information as well as to assess change in deep-sea ecosystems under the impacts of mining as well as climate change.

• Under the UN Fish Stocks Agreement, States Parties acting through the Food and Agriculture Organization of the United Nations (FAO) and regional fisheries management organizations are charged with protecting marine biodiversity from the impacts of fishing. This includes the obligation to protect vulnerable deep-sea ecosystems from the impacts of deep sea bottom fishing on the high seas. Deep ocean monitoring is again crucial to assist with assessing the effectiveness of such measures.

• The United Nations is currently charged with developing a new international legally binding instrument for the conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction under the United Nations Convention on the Law of the Sea. This instrument will, it is hoped, set the platform for monitoring, evaluating and implementing the full range of conservation tools including MPAs, environmental impact assessments. Global cooperation will be essential.

• The United Nations Framework for Climate Change Convention (UNFCCC) and its scientific arm, the Intergovernmental Panel on Climate Change (IPCC) will increasingly need deep-ocean observations as inputs to its 5-year reports and the special report on Oceans and Cryosphere. Deep ocean observations are fundamental to the predictions and confidence levels inherent to the mandate of this organization.

The potential for a planning activity focused on a multi-disciplinary and integrated pilot (or suite of pilots) was discussed as a potential early activity for the DOOS SC. For more information please see Appendix 3.

| Action 25: Increase awareness of the importance of deep ocean observing for existing and future capabilities. |
| Action 26: Build partnerships to make sure that the science is being utilized by the world ocean assessment and other stakeholders |
| Action 27: Highlight a few very sensitive and important scientific questions and ecosystems to the public/policy makers |
| Action 28: Develop partnerships with intergovernmental organizations (DOSI, IPBES, INDEEP, IPCC, WCRP, NGOs – IUCN/CI, others?) |
DOOS 2016 WORKSHOP SUMMARY STATEMENT

With an average depth of more than 3800 m the ocean is largely deep sea. In addition to over 100 nations having deep-sea territory, there are also vast deep areas beyond national jurisdiction. The deep ocean is rapidly changing and subject to growing human impact, intensifying the need for deep observing. Such observing requires an international effort with resulting data accessible across the globe.

The deep ocean focus here includes depths below 200 m with an emphasis on depths below 2000 m. DOOS reflects a first attempt to bring together and coordinate the deep ocean physical, biogeochemical and biological observing communities and observations. EOV specification for deep-ocean applications should proceed including physical, biogeochemical and biological teams. DOOS may play the role of data integrator where existing and newly acquired data are compiled to yield a global view (quality/quantity) of the deep ocean. GOOS, OceanSITES, Argo (especially Deep Argo and Bio Argo), Go-Ship, and SMART Cables are international efforts that can significantly contribute to this effort.

Another DOOS role can be as multidisciplinary data generator, where pilot sites are promoted for physical, chemical, geophysical, biological, and ecological measurements. The concept of integrated pilot activities should be explored, including location or theme foci, towards addressing the multi-and interdisciplinary challenges facing deep ocean research and observation efforts.

Ultimately, the greatest value from deep observing may emerge far in the future; DOOS can provide the potential vision and foresight to provide information for future generations.
## APPENDICIES

### Appendix 1: 2016 DOOS Workshop Attendees

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>Matthew Alford</td>
<td>Scripps Institution of Oceanography</td>
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<td>Ward Appeltans</td>
<td>Intergovernmental Oceanographic Commission of UNESCO</td>
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<tr>
<td>Jim Barry</td>
<td>Monterey Bay Aquarium Research Institute</td>
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<td>Simone Baumann-Pickering</td>
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<td>Fabio Cabrera De Leo</td>
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<tr>
<td>Dave Checkley</td>
<td>Scripps Institution of Oceanography</td>
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<td>Kruti Desai</td>
<td>Consortium for Ocean Leadership</td>
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<td>Yassir Edeebbar</td>
<td>Scripps Institution of Oceanography</td>
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<td>*Albert Fischer</td>
<td>Intergovernmental Oceanographic Commission of UNESCO</td>
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<td>Kristina Gjerde</td>
<td>International Union for Conservation of Nature</td>
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<td>Harriet Harden-Davis</td>
<td>University of Wollongong</td>
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<td>*Patrick Heimbach</td>
<td>University of Texas at Austin</td>
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<td>Bruce Howe</td>
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<td>Alfred-Wegener Institute</td>
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<td>*Greg Johnson</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>Katsuro Katsumata</td>
<td>Japan Agency for Marine-Earth Science and Technology</td>
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<td>Orest Kawka</td>
<td>University of Washington</td>
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<td>Gulf of Mexico Coastal Ocean Observing System</td>
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<td>Todd Martz</td>
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<td>University Corporation for Atmospheric Research</td>
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<td>Patricia Miloslavich</td>
<td>Universidad Simón Bolivar</td>
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<td>Sandor Muslow</td>
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<td>Dean Roemmich</td>
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<tr>
<td>*Sun Song</td>
<td>Institute of Oceanology, Chinese Academy of Sciences</td>
</tr>
<tr>
<td>Adam Soule</td>
<td>Woods Hole Oceanographic Institution</td>
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<tr>
<td>Name</td>
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| Karen      | Stocks  
Scripps Institution of Oceanography                 |
| James      | Swift  
Scripps Institution of Oceanography                 |
| Lynne      | Talley  
Scripps Institution of Oceanography                 |
| *Toste     | Tanhua  
GEOMAR Helmholtz Centre for Ocean Research           |
| Julie      | Thomas  
Scripps Institution of Oceanography                 |
| *Rik       | Wanninkhof  
National Oceanic and Atmospheric Administration       |
| Susan      | Wijffels  
Commonwealth Scientific and Industrial Research Organization, Australia |
| Kristen    | Yarincik  
Consortium for Ocean Leadership                       |
| Nathalie   | Zilberman  
Scripps Institution of Oceanography                 |

*Program Committee Members*
## DAY 1: WEDNESDAY DECEMBER 7, 2016

<table>
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<tr>
<th>Time</th>
<th>Agenda Item</th>
<th>Person</th>
<th>Allocation</th>
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<tbody>
<tr>
<td>8:00</td>
<td>Continental Breakfast <em>(provided)</em></td>
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<tr>
<td>8:30</td>
<td>Welcome from the Director of the Scripps Institution of Oceanography</td>
<td>M. Leinen</td>
<td>5 min</td>
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<tr>
<td>8:35</td>
<td>Introduction to the Framework for Ocean Observing and Essential Ocean Variables</td>
<td>A. Fischer</td>
<td>10 mins</td>
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<tr>
<td>8:45</td>
<td>Day 1: Objectives and Introductions</td>
<td>L. Levin</td>
<td>20 mins</td>
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<tr>
<td>9:05</td>
<td>Participant Introductions</td>
<td>All</td>
<td>30 min</td>
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<tr>
<td>9:35</td>
<td>Deep Ocean Themes &amp; Case Studies</td>
<td><em>Moderator:</em>  P. Heimbach</td>
<td>Format: 12 min for each talk</td>
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<tr>
<td></td>
<td>Observing and modeling climate change/deep ocean roles</td>
<td>B. Sloyan</td>
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<td></td>
<td>Ventilation and Circulation (Transient tracers)</td>
<td>T. Tanhua</td>
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<td></td>
<td>Turbulence</td>
<td>K. Katsumata</td>
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<td></td>
<td><em>Rapporteur:</em> F. DeLeo</td>
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<tr>
<td>10:30</td>
<td>Lunch <em>(provided)</em></td>
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<tr>
<td>11:15</td>
<td>Deep Ocean Themes &amp; Case Studies (Cont.)</td>
<td><em>Moderators:</em>  K. Oguri</td>
<td>Format: 12 min for each talk</td>
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<td></td>
<td>Biogeochemical drivers – nutrients/ oxygen/ carbon cycling/</td>
<td>R. Wanninkhof</td>
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<td></td>
<td>Ecosystem consequences of changing biogeochemistry</td>
<td>N. LeBris</td>
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<td></td>
<td>Seabed mining, oil and gas, carbon sequestration</td>
<td>C. Smith</td>
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<td>Deep Water Fish and Fisheries</td>
<td>T. Koslow</td>
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<td>Biodiversity</td>
<td>H. Kitazato</td>
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<td></td>
<td><em>Rapporteur:</em> F. DeLeo</td>
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<tr>
<td>12:30</td>
<td>Lunch <em>(provided)</em></td>
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<tr>
<td>1:30</td>
<td>DOOS Scope – Defining Scientific Goals</td>
<td><em>Moderators:</em>  H. Ruhl</td>
<td>90 min</td>
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<td></td>
<td><em>Rapporteurs:</em> Y. Eddebbar and J. Barry</td>
<td>P. Heimbach</td>
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<td><strong>Plenary Discussion Questions:</strong></td>
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<td></td>
<td>What scientific questions can a deep-sea observing strategy contribute?</td>
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<td>What synergies result from integrating programs?</td>
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<td>What scientific problems will these address?</td>
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<td>How should this be reflected in the Terms of Reference?</td>
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<tr>
<td>3:00</td>
<td>Break</td>
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<tr>
<td>3:20</td>
<td>State of Deep Ocean Observing</td>
<td>A. McCurdy</td>
<td>20 min</td>
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<td></td>
<td>Review of Community Input to DOOS Consultative Draft</td>
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<tr>
<td>3:40</td>
<td>Overview of Deep-Ocean Observing Inventory</td>
<td>L. Smith</td>
<td>30 min</td>
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</table>
4:10 Overview of National Efforts (One slide per nation)  
\[\text{Moderator: A. Fischer} \]
\[\text{30 min} \]

4:40 Day 1 Wrap-Up  
\[\text{Prep discussion items for Day 2} \]
\[\text{L. Levin} \]
\[\text{20 min} \]

5:00 Reception (a special thanks to Scripps)

7:30 Dinner Off-Site

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**DAY 2: THURSDAY DECEMBER 8, 2016**

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<th>Time</th>
<th>Agenda Item</th>
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<tr>
<td>8:00</td>
<td>Continental Breakfast <em>(provided)</em></td>
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<tr>
<td>8:30</td>
<td>Day 2: Objectives</td>
<td>L. Levin</td>
<td>15 min</td>
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<tr>
<td>8:45</td>
<td><strong>DOOS Essential Ocean Variable (EOV) Overview</strong></td>
<td>L. Levin</td>
<td>90 min</td>
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<td></td>
<td><em>GOOS Panel EOVs vs. Deep EOVs (read-ahead graphic provided)</em></td>
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<td></td>
<td><strong>Physical</strong></td>
<td>B. Sloyan</td>
<td>Format:</td>
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<td></td>
<td><em>Moderator: N. Zilberman/Rapporteur: S. Song</em></td>
<td></td>
<td>10 min talk</td>
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<td></td>
<td><strong>Biogeochemistry</strong></td>
<td>T. Tanhua</td>
<td>20 min</td>
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<td></td>
<td><em>Moderator: F. Janssen/Rapporteur: R. Wanninkhof</em></td>
<td>P. Miloslavich</td>
<td>discussion</td>
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<td></td>
<td><strong>Biology and Ecosystem</strong></td>
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<td><em>Moderator: P. Snelgrove/Rapporteur: H. Harden-Davies</em></td>
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<tr>
<td>10:15</td>
<td>Break</td>
<td></td>
<td>90 min</td>
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<tr>
<td>10:45</td>
<td><strong>Technology Developments</strong></td>
<td>B. Howe</td>
<td>15 min talk</td>
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<td>Sensors</td>
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<td>30 min</td>
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<td></td>
<td><em>Moderator: M. Alford/Rapporteur: D. Checkley (T. Martz)</em></td>
<td>U. Send</td>
<td>discussion</td>
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<td><strong>Platforms</strong></td>
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<td><em>Moderator: S. Baumann-Pickering/Rapporteur: B. Kirkpatrick</em></td>
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<tr>
<td>12:15</td>
<td><strong>DOOS Requirements and Opportunities - Geographic Locations</strong></td>
<td>R. Perez</td>
<td>30 min</td>
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<td><em>Moderator: M. Lankhorst/Rapporteur: R. Perez</em></td>
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<tr>
<td>12:45</td>
<td>Lunch <em>(provided)</em></td>
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<tr>
<td>1:00</td>
<td><strong>Interdisciplinary Task Team Breakouts <em>(Topics Subject to Change)</em> Goal:</strong></td>
<td>R. Perez</td>
<td>90 min</td>
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<td>Set up the teams or working groups that move DOOS forward</td>
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<td></td>
<td><em>Observing Needs – Climate Science and Impacts</em></td>
<td>Group 1</td>
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<td><em>Moderator: L. Talley/Rapporteur: P. Snelgrove</em></td>
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<td><em>Observing Needs – Science for Managing Societal Uses of the Deep Ocean</em></td>
<td>Group 2</td>
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<td><em>Moderator: K. Gjerde/Rapporteur: F. DeLeo</em></td>
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<td></td>
<td><em>Observing Needs - Technology Advances</em></td>
<td>Group 3</td>
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<td><em>Moderator: O. Kawka/Rapporteur: A. Soule</em></td>
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<td><strong>TBD…based on workshop discussions</strong></td>
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<tr>
<td>3:15</td>
<td>Break</td>
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<td>90 min</td>
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<tr>
<td>3:30</td>
<td><strong>Plenary Session - Review Task Team Breakout Results</strong></td>
<td>All</td>
<td>60 min</td>
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<td><em>Moderator: S. Wijffels/Rapporteur: D. Rudnick</em></td>
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<tr>
<td>4:30</td>
<td><strong>Closing</strong></td>
<td>L. Levin</td>
<td>30 min</td>
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<td></td>
<td>Recap Findings</td>
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<td></td>
<td>b. Prep discussion items for Day 3 including Terms of Reference</td>
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### DAY 3: FRIDAY DECEMBER 9, 2016

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<tr>
<td>8:00</td>
<td>Continental Breakfast <em>(provided)</em></td>
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| 8:30 | I. Funding Opportunities and Data Sources - including academic, industry, & government linkages  
*Moderator: K. Yarincik/Rapporteur: S. Mulsow* | K. Yarincik | 30 min     |
| 9:00 | II. Data Management Challenges & Opportunities  
*Moderator: J. Thomas/Rapporteur: J. Swift*  
a. Infrastructure: Data discovery, Access, Transfer, Metadata, Archive  
b. Data Accessibility, Usability, and Interoperability | J. Thomas   | 60 min     |
|      | Format: 10 min talk 20 min discussion                                         | W. Appeltans|            |
|      |                                                                               | K. Stocks   |            |
| 10:00| Break                                                                        |             |            |
| 10:30| III. Day 3: Objectives and Input on Terms of Reference                       | L. Levin A. Fischer | 30 min     |
| 11:00| IV. Assess Next Steps and Deliverables                                       | Planning Committee TBA | 60 min     |
|      | a. Consensus on Priority Issues                                               |             |            |
|      | b. DOOS Directions: Task Team or Working Group Formation                      |             |            |
|      | c. Workshop Recommendations                                                   |             |            |
| 12:00| Lunch *(provided)* – Official Workshop Adjourns                               |             |            |
| 1:00 | Planning Committee Reconvenes from 1 - 5 PM to  
- Summarize deliverables  
- Prepare report  
- Finalize DOOS Terms of Reference  
- Create Action Plan | Planning Committee | 240 min     |
| 5:00 | Planning Committee Adjourns                                                  |             |            |
Appendix 3: Pilot Suggestion

Proposed Multi-disciplinary, Integrated Pilot Deep Ocean Observing Site

Craig Smith, University of Hawaii, Manoa

The Clarion-Clipperton Zone (CCZ) provides a prime location for DOOS sustained observational pilot studies to address multiple DOOS goals related to human impacts in the deep-ocean from climate change (e.g., OMZ expansion) and deep-sea mining, to better understand natural variations and trends in carbon cycling, deep pelagic ecosystems, and benthic ecosystem functions, and to advance the agenda of other GOOS Projects (e.g. Tropical Ocean Observing System (TPOS) 2020 Project).

With respect to TPOS 2020, its First Report (December 2016) 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 fall within the core region of nodule-mining explorations claim registered with the International Seabed Authority (ISA), they span the intense and expanding OMZ of the eastern tropical Pacific, they contain key fisheries populations, and they are representative of some of the largest, and most poorly studied benthic and mid-water biogeographic provinces in the world ocean (see Watling et al., 2013).

Sustained observations of a range of EOVs (from the sea surface to the abyssal seafloor) at or near CCZ locations would help to address key scientific questions relevant to TPOS, DOOS carbon-cycle studies, deep pelagic ecosystems responses to deoxygenation, acidification and human activities, and the impacts of deep-sea mining as follows.

For the Deep Ocean in the Tropical Pacific Observing System:
- Estimate full-ocean-depth heat content anomalies on time scales of one year and longer,
- Detect changes in temperature/salinity characteristics on interannual/decadal timescale in the deep ocean in relation to high latitude water mass variability and formation rates,
- Reduce the present 2000 m discontinuity in ocean observations for improvement of forecast model initialization and ocean data assimilation.

To address key DOOS carbon cycle questions:
- Evaluate carbon inventories in the deep ocean, including the vast Pacific basin
- Constrain natural variations and trends in the biological pump and related carbon remineralisation/sequestration processes, and
- Improve high-frequency EOV observations at fixed-point reference stations.

For deep pelagic ecosystems:
- Elucidate variability over time, and responses to climate change, in deoxygenation, acidification and human activities (e.g. sea-bed 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.
For elucidating the functional importance of animals and microbes in the Deep Ocean:

- Determining how environmental conditions (e.g., water velocity/benthic storms, turbidity, T, pH, O2, POC flux) vary in abyssal ecosystems targeted for mining experience, and
- Explore how this variation influences biodiversity and function?

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.
Appendix 4: 2016 DOOS Workshop Tracked Actions

DOOS Workshop Tracked Actions: December 2016

**Action 1:** Identify and form a DOOS Steering Committee with appropriate disciplinary, programmatic, and geographic representation

**Action 2:** Distribute the list of science questions developed at the workshop and ask the Earth Science Community: Are we missing solid Earth components?

**Action 3:** Distribute the list of science questions developed at the workshop. What needs to be added that will connect with one of the areas identified?

**Action 4:** Distribute the list of science questions developed at the workshop. Are there necessary modifications to the EMSO questions?

**Action 5:** Add-to and complete deep ocean inventory, including mapping features

**Action 6:** Move tracers from Physics to BGC EOV category in Consult Draft

**Action 7:** Create Physics EOV specification sheets; accuracy needs
  - Turbulence, bottom pressure, geothermal fluxes, bottom stress
  - Add relief and topography as Fundamental baseline dataset
  - Add Geothermal considerations

**Action 8:** Specify EOV BGC unique requirements for the deep sea (e.g. accuracy)

**Action 9:** Form a subcommittee to solidify the Biology EOVs

**Action 10:** Place a BGC and Phys representation on subcommittee

**Action 11:** Identify gaps (knowledge, geographic, variables, technical) and emerging systems relative to the key science and societal questions

**Action 12:** Synthesize workshop notes on identified observing requirements and gaps (research, geographic? other?)

**Action 13:** Identify task teams and working groups to address specific gaps

**Action 14:** Write outline and timeline for drafting the community DOOS Science Guidance and Implementation Plan

**Action 15:** Conduct or identify events to connect with stakeholders from various fields (industry, intergovernmental)

**Action 16:** Work with OceanSITES to assist in the identification of locations that provide global coverage
**Action 17**: Develop ways to promote existing opportunities among communities

**Action 18**: Generate one-page write up by the Carbon group, benthic functional group, and the deep pelagic group and consider how they could integrate proposed research

**Action 19**: Create maps by decade of coverage of the EOVs across all disciplines – to underscore the vacuum of observations, updated on 2/yr basis, taking advantage of existing infrastructure and data systems. (Use JCOMMOPS as a resource.)

**Action 20**: Document and post best practices of existing networks (observation techniques, data management) for deep observing, compile and coordinate relevant distribution activities

**Action 21**: Formulate a technology roadmap from the deep observing requirements

**Action 22**: Have the steering committee address tech transfer and tech capacity building

**Action 23**: Create a Data Team

**Action 24**: Conduct a deep ocean data audit (Are delayed-mode data systems capturing data? Audit by country, program, identify contributions to the global challenge, from the major aggregators, track evolution over time. Audit for protocols and standards, QC, connection to aggregators, repositories)

**Action 25**: Increase awareness of the importance of deep ocean observing for existing and future capabilities.

**Action 26**: Build partnerships to make sure that the science is being utilized by the world ocean assessment and other stakeholders

**Action 27**: Highlight a few very sensitive and important scientific questions and ecosystems to the public/policy makers

**Action 28**: Develop partnerships with intergovernmental organizations (DOSI, IPBES, INDEEP, IPCC, WCRP, NGOs – IUCN/CI, others?)
Appendix 4: Round Table Individual Responses (Day 3)

- **Comment:** Would like to focus on low hanging fruit, “white paper” expansion  
  o **Contribution:** Would like to contribute to editing

- **Comment:** Would like to see implementation plan covering the science questions that we created to tie different disciplines together, building the observing network. Difficult to create the integration  
  o **Contribution:** Would like to assist in future project development

- **Comment:** Would like to see 2-3 focused efforts (breakout groups?) to creating a consensus of mega sites (integrate systems) which would lead to pilot studies  
  o **Comments:** Would like to see observation coordination and advocacy

- **Comment:** Would like to see design of instruments, new technology

- **Comment:** Would like to see the coordination of existing observing arrays and data management (DMAC) activities that foster capacity building  
  o **Contribution:** Willing to bring Australian contribution and can help with any process in developing EOVs

- **Comment:** Would like to see a science and implementation plan; can see a path forward in the focused science plan  
  o **Contribution:** Willing to help on the physical and BCG side of that and think about integrating all disciplines through regional sites

- **Comment:** Would like to see DOOS emphasize physical efforts and move them to the forefront and supersites idea. The PO can promote pilot projects on these sites, try new instruments, and expand physical oceanography in a new direction

- **Comment:** Would like to see the strengthening of existing networks for data integration and capacity building—long term  
  o **Contribution:** Willing to contribute in any path DOOS wants to move forward in developing EOVs

- **Comment:** Would like to see a transnational, transdisciplinary deep observing working group—focused on the core niche that no one else is doing  
  o **Contribution:** Happy to help in any way

- **Comment:** Stay focused and keep funding agencies engaged through a balanced interdisciplinary approach (emphasize the need to give something to the agencies that they can grasp)  
  o **Contribution:** Continue to provide support through the Consortium for Ocean Leadership as a node of the distributed project office
• **Comment:** Would like to see DOOS narrow down to something achievable EOVs via interdisciplinary discussions and clarify the connections or differences between GOOS and DOOS
  - **Contribution:** Would like to contribute in the biology realm and pelagic ecosystems

• **Comment:** Would like DOOS to target EOVs already covered and add those that incorporate new variables into the system; and also develop an implementation plan that is both interdisciplinary and focused
  - **Contribution:** Can have the Canadian network inform them about particular EOVs

• **Comment:** Would like to see the development of an implementation plan that includes ecosystem function and structure, but we may need a workshop to look into the break out group projects
  - **Contribution:** Would like to help with future endeavors

• **Comment:** Would like DOOS to develop clear and focused talking points on what we are doing and why
  - **Contribution:** Will continue to support as DOOS Sr. Project Manager

• **Comment:** Would like to see the coordination of all observing systems from a data interoperability level

• **Comment:** Would like DOOS to strategically identify investments in the deep ocean and gaps; bring some data system expertise to the thinking.
  - **Contribution:** Would like to help in future endeavors and provide data expertise

• **Comment:** Would like DOOS to create products that can easily feed into IPCC, IPBES, WOA reporting; an OBIS that can serve DOOS
  - **Contribution:** Engage with support office

• **Comment:** Would like to see the development of more plans for coordinated biology/ecosystem/BGC/physical observation in the water column; zone - depends on funding (coastal sites)
  - **Contribution:** Would like to assist in future endeavors

• **Comment:** Would like to see DOOS as a data integrator; a force for data integration and two-way communication; include geothermal and geochemical inputs into water systems
  - **Contribution:** Can help with data management

• **Comment:** Would like to see a broadening of what GO-SHIP is doing - increase the scientific value through adding capability
• **Comment:** Would like to see the building of an ontology of what is being collected and where; build strategy roadmap, EOV concept is attractive
  - **Contribution:** Willing to contribute to the roadmap and developing EOVs

• **Comment:** Would like to see DOOS advocating the use of existing resources. DOOS can and should facilitate the transition from concept to pilot of new system infrastructure and sensing modalities, e.g., SMART cables and acoustic navigation and thermometry. Widely distributed bottom pressure sensors as part of the system have high value.
  - **Contribution:** Willing to serve on the steering committee

• **Comment:** Would like to see something multi-disciplinary and bridge the gap between biological science and physical sciences and focus on geohazards

• **Comment:** Would like to point out that NSF has been funding instrumentation at a much lower level than they used to
  - **Contribution:** Would like to assist in future endeavors

• **Comment:** Would like to see DOOS focus, not exclusively, but more on global aspects of climate change and ecosystem impact. A global perspective will enable the program to succeed. Development of existing pilot studies and implementation in other key regions. Deep ocean climate variability and change. Will sustain Argo and build deep Argo.

• **Comment:** Support pilot studies in key areas for sustaining global deep ocean observations and provide new scientific question for the steering committee to answer

• **Comment:** Would like DOOS to follow-up on OceanObs’09 recommendations; collaborate across disciplines and share the resources and platforms. DOOS has an opportunity to integrate more closely between more platform-oriented programs. Make best use of the strength of these different programs to improve accuracy, spatial sampling, etc. Bring OceanSITES support to the table and on the steering committee

• **Comment:** Would like to see the use of the WHOI deep submergence facility: opportunistic measurements: DS vehicles traverse the water column - use them as a platform. Room at the table for solid Earth

• **Comment:** Would like to see a science implementation plan that can serve as catalyst to expand deep ocean observations, especially for things that are well along in pilot projects; and be more aspirational.

• **Comment:** Would like a clear understanding of what DOOS is. How-to documents in the field of data management, calibration. Engaged through OceanSITES
• **Comment:** Would like DOOS to help others understand importance of deep sea observations (advocacy); look into gaps areas, we need to connect to societal issues*--but focused on science and money (blue economy)

• **Comment:** Would like a DOOS interdisciplinary approach and identify vulnerable areas from climate change; find data that can fit into this small-scale idea. Would like to include mega sites and technology development/capacity building

• **Contribution:** Willing to help with future workshop

• **Comments:** Would like to see DOOS use a cross disciplinary approach and advocacy with viable assessments of what is going on (globally), find tangible, specific next steps that encompass many different groups
  - o **Contribution:** Can contribute interface with Argo, GOOS, and TPOS. Cannot sit on the steering committee

• **Comment:** Would like DOOS to answer large-scale biogeochemical questions in the deep sea via an interdisciplinary approach including physical, biogeochemical and biological interactions

• **Comment:** Would like DOOS to address funding issues by having a clear vision; be inclusive of regions, countries that share the margin of the oceans;
  - o **Contribution:** Will contribute to become a partner of DOOS, GOOS, anyone who will help us to solve some of our problems

• **Comment:** Provide answers to the fundamental question of what is driving the planet; tying it back to societal benefits; how the deep ocean sustains environment, variables that inform the management. Provide uses, services, implications for human well-being. Identify some variables [indicators] that will inform management
  - o **Contribution:** Would like to help with a policy white paper

• **Comment:** Would like to see DOOS strengthen the science policy interface; identify key gaps; new technology, capacity development
  - o **Contribution:** would like to assist in articulating the solutions that policymakers need.

• **Comment:** Would like DOOS to energize parts of the observing community and find funding

• **Comment:** Would like DOOS activities to connect to a broader segment of the deep ocean observing community
### Appendix 5: Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{3}$He</td>
<td>Helium 3</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>Carbon 14</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>Argon 39</td>
</tr>
<tr>
<td>AABW</td>
<td>Antarctic bottom water</td>
</tr>
<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>AIMS</td>
<td>Australian Institute of Marine Science</td>
</tr>
<tr>
<td>ALOHA</td>
<td>A Long-term Oligotrophic Habitat Assessment</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicles</td>
</tr>
<tr>
<td>BATS</td>
<td>Bermuda Atlantic Time-series Study</td>
</tr>
<tr>
<td>BBL</td>
<td>Bottom Boundary Layer</td>
</tr>
<tr>
<td>BGC</td>
<td>Biogeochemistry</td>
</tr>
<tr>
<td>BCP</td>
<td>Biological carbon pump</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CalCOFI</td>
<td>California Cooperative Fisheries Investigations</td>
</tr>
<tr>
<td>CCZ</td>
<td>Clarion-Clipperton Zone</td>
</tr>
<tr>
<td>CFC</td>
<td>Chlorofluorocarbon</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>Methane</td>
</tr>
<tr>
<td>chl-a</td>
<td>Chlorophyll a</td>
</tr>
<tr>
<td>CLIVAR</td>
<td>Climate and Ocean: Variability, Predictability and Change</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>pCO$_2$</td>
<td>partial pressure of carbon dioxide</td>
</tr>
<tr>
<td>COL</td>
<td>Consortium for Ocean Leadership</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>CVOO</td>
<td>Cape Verde Ocean Observatory</td>
</tr>
<tr>
<td>DELOS</td>
<td>Deep-ocean Environmental Long-term Observatory System</td>
</tr>
<tr>
<td>DIC</td>
<td>N,N'-Diisopropylcarbodiimide</td>
</tr>
<tr>
<td>DNA</td>
<td>deoxyribonucleic acid</td>
</tr>
<tr>
<td>DONET</td>
<td>Dense Oceanfloor Network System for Earthquakes and Tsunamis</td>
</tr>
<tr>
<td>DOOS</td>
<td>Deep Ocean Observing Strategy</td>
</tr>
<tr>
<td>DOSI</td>
<td>Deep Ocean Stewardship Initiative</td>
</tr>
<tr>
<td>DWBC</td>
<td>Deep Western Boundary Currents</td>
</tr>
<tr>
<td>EBSAs</td>
<td>Ecologically or Biologically Significant Marine Areas</td>
</tr>
<tr>
<td>EOV</td>
<td>Essential Ocean Variables</td>
</tr>
<tr>
<td>ESMO</td>
<td>European Multidisciplinary Seafloor and watercolumn Observatory</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>FOO</td>
<td>Framework for Ocean Observing</td>
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<tr>
<td>FRAM</td>
<td>Frontiers in Arctic Marine Monitoring</td>
</tr>
<tr>
<td>GCOS</td>
<td>Global Climate Observing System</td>
</tr>
<tr>
<td>GEO BON</td>
<td>Group on Earth Observations Biodiversity Observation Network</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
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<tr>
<td>GOA-ON</td>
<td>Global Ocean Acidification Observing Network</td>
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<tr>
<td>GOOS</td>
<td>Global Ocean Observing System</td>
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<tr>
<td>GRACE</td>
<td>Gravity Recovery and Climate Experiment</td>
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<td>Acronym</td>
<td>Full Form</td>
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<td>---------</td>
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</tr>
<tr>
<td>HOT</td>
<td>Hawaii Ocean Time-series</td>
</tr>
<tr>
<td>ICUN</td>
<td>International Union for the Conservation of Nature</td>
</tr>
<tr>
<td>INDEEP</td>
<td>International Network for Scientific Investigations of Deep-Sea Ecosystems</td>
</tr>
<tr>
<td>IOC</td>
<td>Intergovernmental Oceanographic Commission</td>
</tr>
<tr>
<td>IOOC</td>
<td>Interagency Ocean Observation Committee</td>
</tr>
<tr>
<td>IPBES</td>
<td>Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>ISA</td>
<td>International Seabed Authority</td>
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<tr>
<td>ITCZ</td>
<td>Inter Tropical Convergence Zone</td>
</tr>
<tr>
<td>JAMSTEC</td>
<td>Japan Agency for Marine-Earth Science and Technology</td>
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<tr>
<td>JTF</td>
<td>Joint Task Force</td>
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<tr>
<td>LED</td>
<td>Light-Emitting Diode</td>
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<tr>
<td>MBARI</td>
<td>Monterey Bay Aquarium Research Institute</td>
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<tr>
<td>MPAs</td>
<td>Marine Protected Areas</td>
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<tr>
<td>N</td>
<td>Nitrogen</td>
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<tr>
<td>NEPTUNE</td>
<td>NorthEast Pacific Time-Series Undersea Networked Experiments</td>
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<tr>
<td>NGO</td>
<td>Non-governmental organization</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>NOC/SOC</td>
<td>North and South Oligotrophic Gyre</td>
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<tr>
<td>N₂O</td>
<td>Nitrous oxide</td>
</tr>
<tr>
<td>OBIS</td>
<td>Ocean Biogeographic Information System</td>
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<tr>
<td>OMZ</td>
<td>Oxygen Minimum Zone</td>
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<td>ONC</td>
<td>Ocean Networks Canada</td>
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<tr>
<td>O₂</td>
<td>Dioxygen</td>
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<tr>
<td>OOI</td>
<td>Ocean Observatories Initiative</td>
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<tr>
<td>POC</td>
<td>Particulate Organic Carbon</td>
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<tr>
<td>RAFOSS</td>
<td>SOund Fixing And Ranging</td>
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<td>RLS</td>
<td>Remineralization Length Scale</td>
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<td>ROV</td>
<td>Remotely operated underwater vehicle</td>
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<td>SCOC</td>
<td>Sediment Community Oxygen Consumption</td>
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<td>SDG-14</td>
<td>United Nations Sustainable Development Goal 14</td>
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<tr>
<td>SF₆</td>
<td>Sulfur hexafluoride</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>ToR</td>
<td>Terms of Reference</td>
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<tr>
<td>TPOS</td>
<td>Tropical Pacific Observing System</td>
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<td>TTD</td>
<td>Transient Time Distribution</td>
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<td>UCAR</td>
<td>University Corporation for Atmospheric Research</td>
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<td>UNESCO-IOC</td>
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<tr>
<td>UNFCCC</td>
<td>United Nations Framework for Climate Change Convention</td>
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<tr>
<td>WCRP</td>
<td>World Climate Research Programme</td>
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<tr>
<td>WOCE</td>
<td>World Ocean Circulation Experiment</td>
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