DEEP OCEAN OBSERVING STRATEGY

Consultative Draft, V5-1

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The Global Ocean Observing System

GOOS

A GOOS Project

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This report was drafted in 2012 and was used as a vehicle to develop, for community consideration, a statement of requirements and an initial strategy for sustained global deep ocean observations.

Version 5-1 of the DOOS Consultative Draft was modified to reflect comments provided during the 2016 community review.

In June 2017 this Consult Draft was provided online in its "final" form to be used as a foundational document for the drafting of the "DOOS Science and Implementation Guide". This Guide will be drafted for initial review and comment in early 2018.

This Report is posted at: http://www.deepoceanobserving.org

NOTE TO READERS: DOOS CONSULTATIVE DRAFT V5-1

Earlier versions of this report were used to support the 2016 DOOS Workshop conducted in December 2016 at Scripps Institution of Oceanography in San Diego, California USA. Leading up to this Workshop the report went under extensive review by the deep-ocean observing community. A large portion of these comments are adjudicated and incorporated into this version (V5-1) of the DOOS Consultative Draft. However, there were some major issues identified, during the community review process that would have required an extensive reorganization or rewriting of this Report. Many of these comments were used to guide the formation of the Workshop agenda.

The 2016 DOOS Workshop Report, agenda, and participant list can be found at the following URL: http://www.deepoceanobserving.org/reports/dec-2016-workshop-report/

Generally, the comments not fully incorporated into is version of the Report can be categorized into the following themes:

- There is a need to refine what is meant by 'deep' as the requirements for measurement depths will vary by discipline and require thoughtful consideration.
- The deep-ocean community needs to create a data plan and supporting information technology strategy that will support user needs.
- As the GOOS EOVs and Panels have been developed and/or matured since the writing of the Consultative Draft Report the DOOS EOVs need to be articulated in this context (and the supporting graphics modified).
- DOOS EOVs for all disciplines require a further review and community agreement. This need is greatest in the Biology and Ecosystem discipline.
- There is a need for greater understanding of solid-Earth or the geological context that drives deep-ocean systems.
- There is a critical need for international cooperation among programs, agencies, and countries.
- The technology development section could be improved by a discussion of Technology Readiness Levels by discipline.
- The Report content should be organized such that it assists funders and resource managers in supporting DOOS activities and initiatives.
- A more robust representation of deep-ocean observing activities across the globe will assist with gap analysis and prioritization.

Section Five, Strategic Roadmap: DOOS Development and Implementation of this Report provides a brief overview of how the 2016 Workshop was used to guide the formation of the Project Steering Committee and Task Teams as well as the Terms of Reference. It is through the ToR and Project structure that the remaining themes and concerns not directly (or thoroughly) addressed in this Report will be addressed by DOOS activities and engagement.

Most specifically, in the spring of 2018 the DOOS Project will provide for initial comment and review a *DOOS Science and Implementation Guide*. This Consultative Draft Report, and the community review comments, will be used as a foundational material for the drafting of the Guide.

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INTRODUCTION

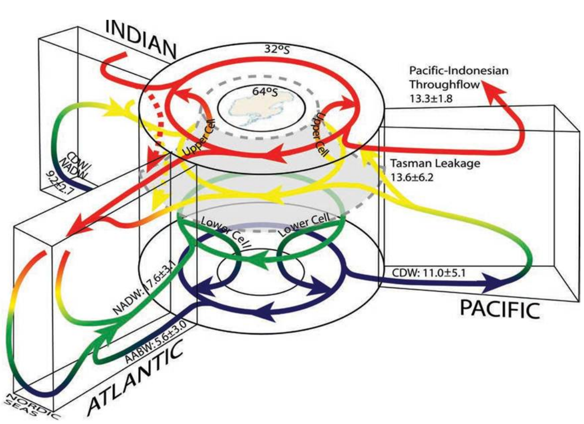
Deep Ocean Observing Strategy

Objective

This report is designed to develop for community consideration a statement of requirements and an initial strategy for sustained global deep ocean observations. The Deep Ocean Observing Strategy (DOOS) is being developed under the auspices of the Global Ocean Observing System (GOOS), and will embrace observations below 200 m. This definition of deep embraces the varied needs (and gaps) of the physical, chemical and biological scientific communities. In particular it recognizes the ecosystem changes that occur below 200 m and the growing importance of the 200-2000 m mesopelagic /bathyal zone. The strategy considers all Essential Ocean Variables (EOVs[1]), regions, and technologies; and in its final form will identify high priority and feasible actions for the next 5-10 years in the deep sea. Ultimately this document is intended to provide a consensus report that aids in individual and national fundraising efforts for elements in support of a deep ocean observing strategy.

Why Deep Ocean Observing?

Thanks to the advances in technology and observing techniques the deep ocean is no longer considered a homogeneous, dark, static environment or even a realm of relic, "fossil like" fauna. Key technical developments have facilitated the investigation of deep-sea life, in particular, the discovery of new ecosystems and the finding of highly diverse deep sea floor habitats (Ramirez-Llodra et al. 2010; Rex and Etter 2010). Through direct and targeted observations, deep-sea submersibles, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), towed instruments, and free-vehicle 'landers' equipped with cameras and biogeochemical sensors have changed our view and understanding of the diversity and activity of the deep-sea realm (Levin and Sibuet 2012). Over the past three decades, we have been able to study cold seeps, deep-water coral and associated reefs, canyons, upwelling margins, oxygen minimum zones, organic falls, hydrothermal vents, basaltic ridges, seamounts, nodule fields, trenches and other types of environments. Developments in marine imaging and acoustics have dramatically revised our understanding of the diversity and abundance of life at midwater depths (Robison 2009, Irigoien et al 2014). Some of the benthic features have shown characteristics of distinctive spatial



A representation of the global overturning circulation. The Southern Ocean connects the ocean basins, through the Antarctic Circumpolar Current, and connects the upper and lower limbs of the global overturning circulation, through water mass transformation. From Lumpkin and Speer (2007), Copyright American Meteorological Society. Reprinted with permission.

[1] EOVs are defined by the Global Ocean Observing System Framework as effective in effective in addressing the overall GOOS Themes – Climate, Real-Time Services, and Ocean Health. variables must be capable of being observed or derived on a global scale, and must be technically feasible using proven, scientifically understood methods. Generating and archiving data on the variable must be affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets. A good example is temperature – see http://ioc-goos oopc.org/documents/EOV%20Specifications/OOPC%20Subsurface%20Temperature%20Specification_v3release.pdf

heterogeneity at scales of meters to kilometers (Levin et al. 2010).

The deep-sea is not static or even stable. A variety of environmental factors contribute to structuring deep-sea geological, physical, and chemical features, as well as biological communities. Process-based ecological studies over the past three decades have demonstrated that the deep-sea is far from being a dormant, buffered system, it responds immediately in time and space to a range of powerful drivers and pressures. These include pulses of sinking organic matter, pollution by hydrocarbons and littering, hydrothermal emissions driven by volcanic activity or mantle-rock alteration, gas escape and mud extrusion from buried methane reservoirs and hydrates, large organic falls such as carcasses and massive wood debris, turbidity currents, shifts in hydrography, stratification, ventilation and ocean currents,, changes in temperature, oxygen, pH/CO_2 and salinity conditions (Glover et al. 2010, Levin and Le Bris 2015). Today, we are far from understanding these changes and the resulting type and degree of physical and biological turnover. Neither do we understand the spatial and temporal scales that just begin to be made more accessible by the use of new technologies.

Scientific evidence now supports the hypothesis that Earth's dynamics, including global change, are affecting the deep sea, and that the deep-sea realm should be observed as a component of the Earth system, as are surface environments. Furthermore, scientific principles of ecosystem assessment and climate observations should be implemented complete with a concept of ocean observation that includes the deep sea. Understanding of this vast realm underpins our ability to address key challenges such as sustainable management of marine resources, understanding ocean ecosystem services in a changing climate, and improving early warning for geo-hazards.

The deep sea is impacted by a broad range of processes which are caused by natural, direct, and indirect anthropogenic drivers. There is much to learn in understanding the relative roles of the different physical, chemical, and biological drivers and processes inducing changes in the deep ocean. Recent studies suggest that rather than viewing the deep sea as one vast ecosystem, we have to comprehend the dimensions of its hydrographical, biogeochemical, and the biogeographical provinces of organisms and their habitats.

Climate Change

The ocean is the memory of the climate system. For the same temperature change and same volume, it stores one thousand times more heat than the atmosphere. The deep ocean (defined here as > 200 m) contains 50 times more carbon than the atmosphere. Ocean seafloor sediments serve as an archive of past productivity and climate regimes, both on land and in the sea. Deep ocean tracer distributions provide one of the very few means of understanding past oceanic flow fields and associated climate histories. Information about the deep ocean is required for the scientific understanding of the Earth System and improved decisions by policy makers such as organized under the World Climate Research Programme (WCRP), World Meteorological Organization (WMO), and United Nations Framework Convention on Climate Change (UNFCCC) and its associated science body, the Intergovernmental Panel on Climate Change (IPCC).

The oceans have taken up about 93% of the enormous amount of thermal energy accumulating in the Earth's climate system over the last four decades (IPCC, 2013; Rhein et al. 2013). The sparse array of global repeat hydrographic data collected by CLIVAR and GO-SHIP suggests that the deep ocean below the 2000-m sampling depth of core Argo, is an appreciable contributor to that thermal energy storage since the 1990s, when World Ocean Circulation Experiment (WOCE) established a high-quality baseline from which changes can be measured. Understanding how much heat the globe is taking up and where (how deep in the ocean) is vital to understanding how much- and how fast the Earth will warm with increased greenhouse gas concentrations.

Deep ocean salinity is also variable, with observed freshening in the bottom waters around Antarctica in recent decades (Purkey and Johnson 2013), possibly reflecting increased rates of glacial melt and perhaps changes in the southern limb of the global Meridional Overturning Circulation (MOC). Measuring and understanding changes in this global circulation feature is a challenge that is being undertaken in the North Atlantic, but data collected outside that ocean basin suggests substantial variations in the portions around Antarctica. We also need to capture short-term components of these changes which reflect or induce major shifts in the circulation regime, such as extreme dense water convection events, large storms and hurricane effects on vertical mixing.

The Deep Western Boundary Currents (DWBCs) of the MOC are part of a global-scale deep ocean current system. Roughly equivalent volumes of dense water sink in the North Atlantic and Antarctic limbs of the MOC and are transported to distant ocean basins. Despite their importance, long-term repeated direct velocity observations of the DWBCs in the Atlantic exist only in a few locations in the North Atlantic. A decade of data from a trans-Atlantic moored array at 26.5°N reveals significant variability of the MOC and DWBC from weekly to decadal time-scales including an overall reduction in the MOC with time (Srokosz and Bryden 2015). The strong DWBC transport variability and the significant variability that still exists in the deep ocean even when integrated across the entire western basin out to the Mid-Atlantic Ridge, demonstrates clearly that the deep layer is quite energetic (Drijfhout et al. 2011) and reinforces the concept that the basin-scale MOC-salt feedback determines whether the thermohaline circulation is stable or unstable. More robust estimates of MOC-trends can be made by combining sections in the North and South Atlantic, the sign of salt flux at 35°S can be used to determine the stability of the MOC; slight changes in position of deep boundary currents can have large impacts. For example, warming due to shifts in the Gulf Stream over the NW Atlantic margin may be dissociating buried gas hydrates and releasing massive quantities of methane (Phrampus and Hornbach et al. 2012) with consequences for microbial and animal production (Boetius and Wenzhoffer 2013). Drawdown North Atlantic deep water with declining pH and subsequent transport by boundary currents exposes deep-water corals and other ecosystems to ocean acidification (Gehlen et al. 2015). Conversely, calcifying organisms are found in areas below their mineral saturation state (Lebrato et al. 2016) and so may provide clues to the limits of possible adaptation. In this regard, deep basins of semi-enclosed seas may be considered at the leading edge of climate change-driven major ecological shifts (e.g. Baltic Sea, Cariaco Sea, Mediterranean Sea) and lead to unexpected synergies.

Ocean warming induces declines in oxygen solubility, increases thermal and salinity stratification which reduces ventilation, and increases respiration. Together these are producing ocean deoxygenation globally (Keeling et al. 2010) this is most severe in intermediate waters of 100-1000 m (Stramma et al. 2010; Helm et al. 2011). Furthermore, warming and freshening of seawater causes a rise in sea levels. Hence the deep ocean temperature and salinity changes originating in the North Atlantic and Southern Ocean contribute to sea level variations, globally and regionally. To fully understand sea level rise and the sea level budget, it is necessary to routinely and globally measure temperature and salinity the half of the ocean volume not currently sampled by core Argo; the ocean deeper than 2000 m. Measurements of oxygen and the carbonate system at these depth are also critical for understanding deep ocean mitigation of and adaptation to climate change.

Geo-hazards and a variety of geological 'events' that take place in the deep ocean can pose hazards to humans. Many of these arise from tectonic activity that triggers earthquakes, massive slides and turbidity currents, volcanic eruptions, and tsunamis. Methane dissociation and mud volcano eruptions can destabilize margin sediments, initiate debris and liquefied sand flows which may pose hazards to deep infrastructure (oil and gas rigs, cables) (Maslin et al. 2010).

Growing Human Presence

Due to the overexploitation of resources on land and the rising costs associated with their use, there are an emerging number of potential economic opportunities for industries focused on the use of deep-sea resources (Ramirez-Llodra et al. 2011). As these vary in scope and feasibility, their impact needs to be monitored through a range of observation techniques. Among these activities are marine capture fisheries, bio-prospecting, oil and gas extraction, and mining for seabed minerals (Mengerink et al. 2014):

Marine Capture Fisheries: Deep-water fisheries were established in the 1960s and 1970s, with the development of new and more robust fishing gear. Since that time, fishing depths have increased and it is now routine to collect fish below 1000 m depth (Watson and Morato 2013). These fisheries are concentrated in areas that have some of the greatest biological significance in the deep sea.

Seamounts, cold water coral reefs, continental slopes including canyons, are among the deep-sea habitats where currents and high surface productivity insure an attractive food supply. This constant supply of food results in large fish aggregations that have consequently attracted fishers. Deep-water trawling leaves a massive environmental footprint, and now covers nearly one-fifth of the continental slopes. It is especially destructive in areas of vulnerable habitats such as corals and sponge reefs. Deep-sea fish often have lifespans of 100 years or more (Norse et al. 2012) whereas corals may live for thousands of years, making recovery from fishery disturbance exceedingly slow. As early as 1997, Merrett and Haedrich (1997) considered some deep-sea fish stocks as nonrenewable resources. Additionally, these areas are also characterized as rich benthic fauna habitats (Buhl-Mortensen et al. 2010), where video, photographic, and acoustic surveys have revealed evidence of damage to these fragile habitats due to fishing (Puig et al. 2012).

Bioprospecting: The high degree of biodiversity found in the oceans creates opportunities for collecting marine organisms for a suite of pharmaceutical, health and industrial applications. The deep sea represents a vast genetic reservoir, offering many avenues for industrial and pharmaceutical interest and potential exploitation as this sector has been growing (Arnaud-Haond *et al.,* 2011; Broggiato et al., 2014a). Major opportunities in the deep sea stem from the diverse populations of microbes in habitats which have adapted to extreme environmental conditions such as hydrothermal vents (hot, acid or strongly alkaline, basic, high concentration of cold waters) and polar waters (freezing), where these physiological adaptations have resulted in novel properties that may prove to be a resource for industrial biotechnology and even climate remediation (Mahone et al. 2015). The potential for the harvest of biologically formed compounds and genetic resources occurs in areas such as cold-water coral reefs, sponge gardens, seamounts, cold seeps, organic falls and hydrothermal vents. There is also the potential for discovery of novel biomaterials with military and industrial applications, (e.g., Yao et al. 2010).

Oil and Gas Extraction: The extraction of hydrocarbon energy from the oceans has moved progressively deeper in recent decades (Merrie et al. 2014). Oil and gas exploitation is routine in deep waters to 3000 m, and extraction from reservoirs deep below the seabed will continue to increase. While the exploration of gas hydrate deposits may offer new research opportunities, higher prices for ocean-based energy are expected to make exploitation of these resources in deeper areas economically viable. However, as shown by the Deep Water Horizon accident, along with deep-sea drilling are significant safety, technological, and environmental risks (Merrie et al. 2014, Cordes et al. 2016).

Waste Disposal: The deep-ocean is now the recipient of many different forms of human waste. Terrestrial mine tailings full of toxic metals and compounds are routinely disposed of on deep margins (at 500-1000 m or deeper). This activity occurs at 14 locations in 6 countries, and often goes unmonitored (Ramirez-Llodra et al. 2015). Plastics are present throughout much of the deep sea in many sizes and configurations, and organic and pharmaceutical contaminants are recorded in deep-sea species when measured (Ramirez-Llodra et al. 2011). Earthquakes and tsunamis, typhoon and hurricanes release large amounts of terrestrial and coastal debris that often end up in the deep ocean. These accidental inputs add to the most persistent fraction of pollutants (e.g. POP, plastics) that accumulate in deep waters. Major accidents that release radioactive waste, oil spills, and other contaminants increasingly threaten deep-water ecosystems.

Emerging Energy Sources: In tandem with the exploitation of oil and gas reserves comes increased pressure to find alternative sources of energy, and to remove fossil fuel-derived greenhouse gases from the atmosphere. The ocean offers the potential for renewable ocean energies, such as wave, geothermal, and ocean-thermal sources. Options such as OTEC (Ocean Thermal Energy Conversion) involve the generation of thermal gradients created by bringing up cold deep ocean waters into warm surface waters. Due to the creation of food and fresh water as byproducts these applications growing in interest in tropical and subtropical waters (Fujita et al. 2011).

Geoengineering and Carbon Storage: The rapid rise in atmospheric CO_2 and its many consequences have led society to consider a host of direct interventions loosely termed geoengineering. Some involve using of the deep-sea as a storage venue (e.g. for CO_2). Deep-sea deposition of bio-carbon like agriculture waste and charcoal is also currently under consideration. Others, such as solar radiation management would affect the deep sea less indirectly but would eventually do so through changes in MOC as well as the organic and inorganic biological pumps. Retro-actions on climate however require thorough investigations. Together with adverse effects on biota comes a potential reduction of yet overlooked deep-sea carbon pumps (e.g. Roth et al. 2014; Higgs et al. 2014); the release of greenhouse gasses such as methane and N_2O deserve careful attention.

Mining for Seabed Minerals: Minerals occur on the seabed in a variety of forms that include metals (Mn, Ni, Co, Cu, Zn, Pb, Ag, Au, Pt and rare earths) increasingly valued for industrial and societal uses. Among these, polymetallic nodules, seafloor massive sulfides (SMS), and cobalt crusts are being targeted for exploration in international waters (Levin et al. 2016). The International Seabed Authority (ISA) has awarded 27 contracts to 19 countries for exploration in the Atlantic, Pacific and Indian Oceans, however in 2016 there is no commercial exploitation yet underway. Other relevant minerals of potential commercial interest include phosphorites found in present or past upwelling zones, metalliferous sludge in the Red Sea, and rare earth metals, which have been found in the sediments and nodules of the central Pacific Ocean. Numerous questions exist about the environmental impact of large scale, and commercial mining and how to manage these (Le et al, 2016); answering many of these will require long-term observations.

The next generation of tools and techniques for observing the deep ocean will need to be developed to address existing uncertainties about patterns of diversity, deep ocean responses to climate change, and human impact. Species composition and the structure of deep-sea communities are influenced by many factors such as short term natural events like pulses of organic matter (influencing recruitments periods), by long term changes of decadal and interdecadal scales in oceanic patterns (PDO, NAO, and El Niño Southern Oscillation (ENSO), e.g. Smith et al. 2009) which cause large scale changes in temperature and food supply, and by drastic changes due to tectonic or geological processes (such as underwater earthquakes and undersea volcanoes). In addition, uncertainties associated with indirect and direct human-induced drivers of change in the deep sea also need to be taken into consideration. These include consequences of ocean warming on circulation, chemical content (e.g., O_2, nutrients, pH, CO_2), and productivity and export fluxes, and local hydrodynamic conditions, along with the impacts of resource extraction (e.g. fish, gas and oil, minerals), waste disposal, light and noise (e.g. associated with ship traffic, energy and mining operations), or other potential risks (e.g. seabed CO_2 storage).

Methodology and Structure of Report

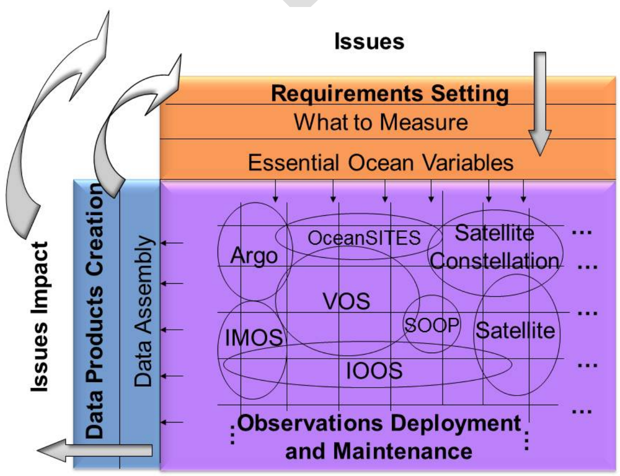
This report develops a statement of requirements designed to lead to an initial strategy for sustained global deep ocean observations; considering ocean variables, regions, and technologies which will extract high impact and feasible actions. The statement is framed in alignment with the Framework for Ocean Observing (Lindstrom et al. 2012). The Framework approach contends that to maintain a global ocean observing system that is fit-for-purpose, the outputs of the system must properly address the issues that drove the original need to measure an ocean variable, and establish a feedback loop of assessment that must be maintained by community agreed-upon processes.

In order to establish this concerted community effort, the Framework also recommends that ocean observing activities be organized around community-defined and selected Essential Ocean Variables (EOVs). An EOV is defined as a variable or aspect of the ocean that the ocean observing community agrees must be measured in order to further scientific understanding of the ocean and Earth systems and their impact on society.

An important caveat related to the use of the term "essential": In the context of EOVs "essential" is not to be confused with "minimal," as has been used in defining baseline requirements for some observing projects, programs, missions, platforms, and networks. In these instances the use of the term "minimal" and in some cases "essential" refers to the measurements required to meet the scientific goals of a geographic and/or ocean phenomenon focused-system. Here we address what the science community agrees are "essential" ocean variables (EOVs) to be measured in order to address societal and environmental pressures. Based on this rationale the scientific and decision-making- community agree that these should be a part of a global, sustained ocean observing system.

The Framework further suggests the community needs to engage in ongoing dialog to define the measurement requirements of an EOV, as well as the observational elements (technologies and techniques), and the data and information products required to meet user needs. In making these assessments, the community is asked to evaluate the requirements, observational needs, and data and data products according to their readiness levels.

As suggested according to the Framework or systems approach, the criteria for evaluating new components for possible inclusion into the global ocean observing system will be in terms of their readiness level. These levels are addressed in three broad categories: concept, pilot and mature. During the concept phase, ideas are articulated and peer-reviewed. During the pilot phase, aspects of the system are tested and made ready for global scale implementation. At maturity, they become a sustained part of the global ocean observing system. For each component of the system requirements, observations, and data projects will need to be matured based on ocean science community peer-review, testing, and agreement on best practices.



This report examines the needs of three broad and interacting disciplines within ocean observing communities, the global climate and physical process community, the carbon and biogeochemical community, and the ecosystems and biodiversity community. It articulates common areas of need and address relevant observation scales that require integration across these communities. It explores strategies and tactics for further coordination and potential collaboration. By aligning needs according to a common nomenclature and agreeing to the terms that will result in an optimally functioning system, the community is better able to examine and agree on areas where sustained activities are justified, and where actions for improvement or maturation are needed.

In Part One of this report each of the communities, listed above, explores the societal issues that drive the need for sustained deep ocean observing. The report then provides an overview of the scientific questions that have been formulated in relation to these issues.

Part Two presents the initial articulation of EOVs for each of the three communities. This discussion is framed in the context of the readiness level of the Requirements and where there is a need for further community buy-in and/or further definition or refinement of the EOV.

Part Three provides an overview of the observing elements (sensors, platforms, and networks) currently in place, where platforms and technologies are meeting the needs of the system, and where there is a need for improvement or development.

Part Four discusses guidelines for a deep-ocean data and information policy and management philosophy. This section explores the impact and benefit of the open and free exchange of data to information products and models. It provides examples of how shared data benefits the scientific communities and generates an opportunity for synergistic discoveries across the system.

Part Five Provides the initial DOOS Project structure and Terms of Reference (ToR). The Steering Committee and initial Task Teams are created which will conduct the Project ToR. An initial flagship product of DOOS will be the Science and Implementation Guide (Guide). The Project will also articulate suggestions for integrated, multi-disciplinary pilot sites. Based on the contents of the Guide document and the Pilot site suggestions, a roadmap for coordinated DOOS activities globally.

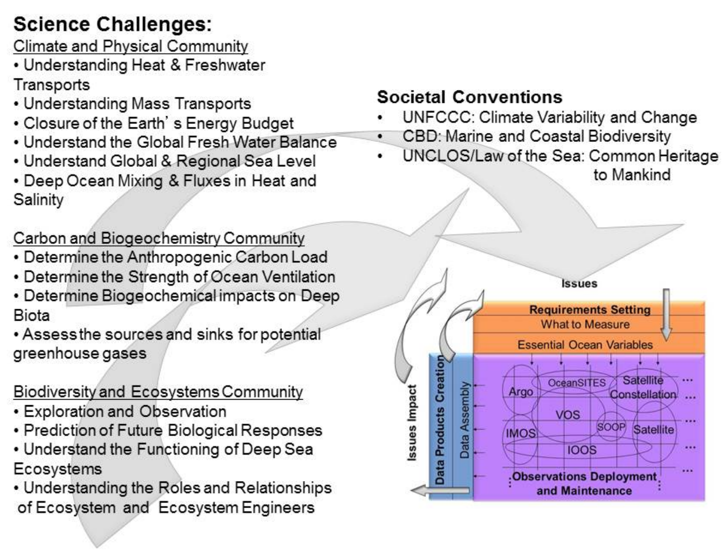
PART ONE

Societal Rationale and Science Challenges

Introduction

The understanding and monitoring of natural and anthropogenic Earth processes that contribute to climate cannot be accomplished by a single program, agency, or country. Only through international cooperation can we collect and share data and knowledge essential for increasing our understanding of Earth's climate and the ecosystems adapted to it. These actions are essential to provide the climate information required by the United Nations Framework Convention on Climate Change (UNFCCC), with the objective "to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

In most regions of the world's ocean (much less the deep ocean), seafloor habitats, currents, water properties, mixing rates, and their variations are not well known. Increased spatial and temporal coverage for accurate measurements of the velocity, temperature, and salinity of the deep ocean will increase our understanding of the ocean's circulation system of surface and deep currents connecting ocean basins sometimes termed the MOC. Much is to be learned about the MOC, its impact on the long-term variability of warming and freshening, its contribution to sea level rise, to deep patterns of mixing, and the influence of deep-ocean geothermal processes on the MOC and deep-water properties. An increased understanding of this circulation system will play an important role in our ability to constrain climate models. Models require knowledge of transport and mixing processes at high regional and temporal resolution and at all depths. Their predictions are a critical prerequisite to testing hypotheses related to past, present, and future climate change. These model outputs are vital to improved decadal-to-century, global and regional projections of variations in temperature, precipitation, and sea level.



The Role of Models

The role of models and their data needs are an important consideration when designing a deep ocean observing system. First, given their role in trend detection, some models provide estimates of variables not accessible through direct measurements. They also provide an extrapolation function extending observations and providing estimates of the granularity needed to assess signal-to-noise ratios of climatically sensitive variables. Constrained by direct measurements, models often provide dynamic interpolations consisting of sparse observations of many types -- with the goal of providing a consistent depiction of changes in the ocean. Finally, models are a pivotal component for decadal to multi-centennial prediction studies. They require knowledge of applicable initial deep ocean conditions that are often associated with processes that control changes in ocean heat content and the storage of tracers.

As mentioned above, for the purposes of trend detection, and spatial and temporal sampling is an important ocean observing system design concern, (Wunsch and Heimbach 2014). Current model analysis using former parameter observations, suggests that in order to be optimally effective, and in some instances to be minimally effective, some regions of the deep ocean may require spatial sampling below 2000m at frequencies equal to that of the core Argo network, currently measuring above 2000 m. This is suspected for specific eddy-active regions that could be used to determine deep steric height variability and low-frequency trend detection, (Ponte 2012).

Next, for the modeling community, quantification of the deep ocean's heat content and associated trends are crucial for closing the Earth's energy budget. Climate model simulation of vertically non-uniform rates of heat absorption and storage may provide important clues to resolving surface heat imbalances which have become apparent in some studies, (Meehl et al. 2011, Palmer et al. 2011). As demonstrated by the variability among estimates, attempts to quantify heat content changes from multi-decadal reanalysis, (e.g., Carton and Santorelli 2008) or otherwise data-constrained models (e.g., Song and Colberg 2011), while suggesting deep ocean warming, are hampered by very large remaining uncertainties, (Stammer et al. 2010 and Masuda et al. 2010; Kouketsu et al. 2011, Wunsch and Heimbach 2014). Despite this, possibly due to reduced production of cold and dense deep and bottom waters around Antarctica, a consistent picture emerges across different studies of abyssal warming. Unfortunately, these results remain difficult to reproduce in models given these highly sensitive processes are either significantly unresolved or are poorly represented in the models, (Heuze et al. 2013; 2015). The constraint of models with better observations is a key to improved process representation and for increased confidence in model results.

The growing interest in decadal-to-centennial scale predictions or projections, (e.g., Cane, 2010) also places increasingly stringent demands on suitable initial conditions – as most current model predictions are influenced by artificial model drift, (Hurrell et al. 2009; Meehl et al. 2009). Today, decadal prediction studies remain inconclusive given uncertainties related to whether or not deep ocean conditions have been sufficiently constrained. Predictability studies suggest that changes in deep ocean density (due to eddy noise) may trigger responses in climate indices sufficiently large enough to limit their accuracy to less than a decade, (Zanna et al. 2012). The ocean observing community is challenged to consider the requirements of predictions studies and address the capacity for models to expand the predictability horizon.

Climate and Physical Observations

Deep-ocean currents, deep-reaching mesoscale eddies, as well as deep mixing contribute to the MOC and the global redistribution of temperature, salinity, and other water properties including nutrients, oxygen, and carbon. Deep-ocean warming and freshening are important consequences (and predictors) of climate change, and influence patterns of sea level rise. The understanding of climate variability and ocean physics sets stringent requirements for upper ocean observations. These requirements are even more exacting in the deeper ocean; understanding deep circulation, water properties, and their variability requires knowledge of spatial patterns of mixing including the influence of seafloor topography, and even the influences of geothermal energy fluxes at the sea floor.

High-Level Mandates

Information about the influence of the ocean on climate is at the heart of what are often referred to as climate services. Improvement of these services requires information regarding changes in the deep ocean circulation, its impact on sea level, oxygen, and the up-take of CO_2, heat, and freshwater. Today observations are critical for the generation of climate information and the creation of a foundation for effective decision-making and subsequent policy. Sea level rise is one of the most immediate and inexorable results of climate variability and change, and may pose severe threats for many nations. Critical to the mitigation of these threats are accurate global and regional projections of sea level. Policy makers rely on climate scenario information compiled by the science community. Today decision-makers regularly rely on projections from the science community's coupled climate models. Researchers are currently developing seasonal to decadal forecasts using these models initialized with current conditions and increasingly including baroclinic internal tidal forcing.

Sustained observation and analysis of the deep ocean and its changes are necessary for climate research. Deep ocean studies are central to our understanding of the climate system. Ongoing research is required regarding the Earth system's energy imbalance, sea level rise, the global hydrological cycle, ice cover, dust input, transport of land materials, and other interactions such as those among the oceans, atmosphere, and land, and the cryosphere. Central to several of these topics are the ocean transport of heat and freshwater, deep-water mass formation, and ocean transports.

Temperature, salinity, carbon species, oxygen, and other ocean measurements are insufficient in spatial and temporal coverage. Many of these parameters are presently sparsely and infrequently measured on a global scale, primarily by ship borne repeat hydrography (Talley et al. 2016). This situation holds especially true at depths below 2000 m, which is the current limit of core Argo floats (i.e. those measuring only temperature and salinity to 2000 m depth), although there are now a small number of Deep Argo floats that sample to 6000 m. Thus, despite advances over the last 20 to 40 years, the budgets for global sea level related to contributions from global heat content changes and the addition of mass through melting land-ice are not adequately constrained by deep ocean observations. If the World Climate Research Program (WCRP) and similar organizations are to respond to society's need to better understand changes in climate and provide improved estimates of changes over the next decade, the existing observing system must be expanded to routinely sample the full depth of the global ocean.

Science Challenges

There are several challenges facing the scientific community, related to improved decision making and a fit-for-purpose observing system well equipped to address societal needs. The first challenge is to measure and understand deep-ocean circulation and ventilation and its variability. The MOC is comprised of bottom and deep waters that spread out from their high latitude sources (in the sub-polar North Atlantic and around Antarctica) and return flows of less dense water. Nearly equal volumes of dense waters sink in the North Atlantic and Antarctic limbs of the MOC, and are transported to distant ocean basins. Repeated hydrographic sections, moored instrument time-series, and ocean models have revealed circulation variability in the deep western boundary currents and MOC (Kouketsu et al. 2011; Cunningham et al. 2010), which suggest that climate variability may be rapidly communicated to the global deep ocean via boundary currents (Masuda et al. 2010, Heimbach et al. 2011). Today most of the long-term observations of deep western boundary currents are in the western Atlantic Ocean; more observations in other oceans are required to assess deep ocean circulation variability.

Closely associated with ocean circulation is the measurement of transient tracers (e.g., CFCs and SF_6, tritium, ^{3}He, and ^{14}C), which offer an unprecedented opportunity to study ocean ventilation and its time scales (Fine 2011). Through the use of direct carbon observations it is difficult to separate the small anthropogenic CO_2 component from the large reservoirs of natural carbon. Ocean measurements of nutrients, oxygen, and transient tracers are useful for that purpose. Recent, advanced analytic techniques which pair transient tracers now allow scientists to quantify better anthropogenic CO_2 input into the deep ocean.

Closing of the Earth's energy budget[2] is vital in order to quantify climate variability and to accurately monitor, assess, and predict human induced climate change (e.g. Hansen 2005, Wunsch 2005, 2016, von Schuckmann et al. 2016). The global ocean is by far the largest heat reservoir in the Earth system, as it accounts for the absorption of an estimated 93% of the increase in total energy associated with greenhouse gas warming (Rhein et al. 2013). Recent studies based on a combination of observations (Purkey and Johnson 2010), data assimilation (Kouketsu et al. 2011, Wunsch and Heimbach 2014), and model simulations (Katsman et al. 2011, Palmer et al. 2011) have all emphasized the importance of ocean heat content changes at depths below 2000 m. Understanding both the North Atlantic Deep Water and the Antarctic Bottom Water formation rates and their global property changes are a critical for making assessments of global heat budget dynamics to inform climate change policy.

Changes of freshwater input into the deep and bottom water formation regions at high latitudes of North Atlantic and around Antarctica reflect changes in the global freshwater balance. These changes drive variability in deep circulation by affecting the properties of dense water sinking in both the northern and southern limbs of the global MOC as well as the abyssal circulation itself. Repeated hydrographic observations indicate that Antarctic Bottom Water has significantly freshened and become less dense since the late 1960's (e.g. Rintoul 2007) and North Atlantic Deep Water exhibits large decadal temperature and salinity variations (e.g. Yashayaev 2007). These deep and abyssal variations reflect changes in the processes that control freshwater in the high latitudes (Carmack et al. 2016), namely evaporation versus precipitation (Rawlins et al. 2010), sea ice production and export (Serreze et al. 2006), and glacier and ice sheet melting (Hanna et al. 2013).

Accurate understanding and projection of future sea level change will first require the quantification and analysis of observed sea level changes, including deep ocean steric height variability (Ponte 2012), warming and freshening (e.g., Wunsch et al. 2007). Global Mean Sea Level (GMSL) rise is almost certain to be a devastating consequence of human induced climate change. Seawater will likely continue to expand due to increased ocean heat content, along with the mass addition to the oceans associated with melting of land-based ice (e.g. Hanna et al. 2013). Sea level rise will vary by region and in some areas it may be much larger than the global mean, as there are several factors involved, such as lateral shifts in ocean circulation, gravitational effects due to mass redistributions, and post-glacial changes in basin geometry (e.g., Milne et al. 2009, Stammer et al. 2013). While deep ocean warming and freshening already play an appreciable role in local sea level variability (Purkey and Johnson 2010; Kouketsu et al. 2011), it is expected that warm deep ocean water will play an increasingly important role in global sea level rise as the water column warms and expands over centuries to millennia in response to changes in Earth's radiation budget (e.g. Meehl et al. 2005).

Vital to the closure of the global MOC is the study of the mixing of mass, heat, salt and other characteristics, shifting upward across water property planes in the abyssal flow (e.g., Ferrari and Wunsch, 2009, Mashayek et al. 2015). Today the limited number of turbulent mixing estimates in the abyssal ocean are the result of observations from specialized ship-based profilers that show enhanced mixing above rough seafloor topography (Polzin et al. 1997, St. Laurent and Thurnherr , 2007). However, in most instances, the strength of deep-ocean mixing has been estimated from relatively sparsely sampled temperature and salinity profiles (Sloyan 2005, Jing and Wu 2010). Observing system capacity would be greatly enhanced through the expanded use of deep profiling floats and gliders (Wu et al. 2011, Beaird et al. 2012), conducting missions and measurements that bridge the gap between these limited ship-based, fine and microstructure observations at specific ocean sites.

[2] Measuring/estimating all cross boundary fluxes, which then must equal time rate of change of internal storage (a control volume). For the earth/ocean, the surface heat fluxes are notoriously difficult to measure (at best 10 W/m^2 ; we need 0.1 W/m^2) so, we depend on measuring the change in the volume heat content because it is "easier" to measure and infer the fluxes.

Finally, another factor that drives ocean circulation is that the Earth's interior steadily provides heat to the deep ocean through the seafloor. Along the crests of active mid-ocean ridge systems such as the East Pacific Rise this flux of heat can reach 0.3 W m^{-2} (Davies, 2013). While this energy is slight compared with surface air-sea heat fluxes, models of the abyssal circulation in such regions (Joyce and Speer 1987, Hautala and Riser 1989) have shown that upward convective velocities associated with deep geothermal heating can significantly alter the deep flow and induce gyres at scales of over a thousand kilometers. Even typical abyssal plain geothermal heat flux, 0.05 W m^{-2} (Davies 2013) can have a considerable effect on the abyssal circulation and water properties in remote regions (Joyce et al. 1986). Modeling studies suggest that background geothermal heating makes a substantial contribution to the structure of the large-scale abyssal circulation, potentially altering the strength of the MOC (Adcroft et al. 2001; Emile-Geay and Madec 2009) and impacting abyssal heat content estimates from global state estimation products (Piecuch et al. 2015).

Carbon and Biogeochemistry Observations

The variability and change of transport, turnover, and storage of inorganic and organic carbon, and other elements in the deep ocean are controlled by ocean physics, chemistry, and biology. Changes in carbon inventory and fluxes in the deep ocean can be significantly slower than in the upper water column due to the spatial separation from biogeochemical and physical forcing near the surface. However, in part due to its vast volume, even these small changes can have an appreciable effect on global biogeochemical mass balances, and the storage of anthropogenic carbon. Improvement in the quantification of biogeochemical changes in the deep ocean is imperative in order to understand the Earth system, particularly over centennial and longer timescales.

High Level Mandates

Sustained observation of the deep ocean is critical for a plethora of operational activities, as well as research programs studying climate variability and prediction, and changes in carbon content. National, international, and organizational studies have determined the need for deep ocean observations with an emphasis placed on periodic observations of hydrographic variables, CO_2 system parameters, and chemical tracers throughout the water column.

In support of this, the US Carbon Cycle Science Plan (2011) articulated the need for large-scale, systematic observation and study of the invasion of anthropogenic carbon in the ocean. This requirement has been recognized internationally by a number of countries which occupy areas of deep ocean study which are now actively recommending repeat deep hydrographic observations in these areas; among them are Australia, Canada, France, Germany, Japan, Russia, the United Kingdom, and the United States.

Responding to this need, a standing international repeat hydrography science group has been assembled under the CLIVAR Global Synthesis and Observations Panel (GSOP), the International Ocean Carbon Coordination Project (IOCCP) and the SOLAS/IMBER Carbon Group (SIC). This group has additional endorsement from Coordination Group of the IOC-WMO Joint Technical Commission on Oceanography and Marine Meteorology (JCOMM) and the GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC). The IOCCP and SIC have jointly created an advisory Group On SHIP-based repeat hydrography the Global Ocean Ship-based Hydrographic Investigation Program (GO-SHIP). This group brings together interests from physical hydrography, carbon, biogeochemistry, and other users and collectors of hydrographic data such as Argo and OceanSITES, to develop guidelines and provide advice for the development of a globally coordinated network of sustained ship-based hydrographic sections designed to become an integral component of the sustained global ocean observing system.

Science Challenges

Despite widespread community support, to date hydrographic and biogeochemical changes in the deep ocean below 2000 m have not been fully explored. The completion of the first decadal survey under auspices of the CLIVAR/ CO_2 repeat hydrography program is offering the first observational glimpse of changes in biogeochemical parameters in the deep ocean on these time scales. This study shows that anthropogenic and climate change signals are starting to manifest themselves at depth (Talley et al. 2016, Hassoun et al. 2015).

The challenge remains that even with improvements in technologies and techniques most changes in deep ocean signals are still difficult - even impossible to detect. In order to assess CO_2 changes, due to natural variability versus those that are human induced, it is necessary to first observe the naturally occurring changes related biogeochemical parameters such as oxygen, chlorofluorocarbon, and natural tracers such as noble gas saturation states and isotopic ratios of carbon and nitrogen, as well as the elements of the carbonate system that inform on ocean acidification. Observation of tracers and the output of numerical general circulation models suggest that much of the changes observed are caused by the penetration of anthropogenic CO_2 into the deep ocean primarily following the major pathways of the MOC.

Generally, model results agree with observations taken above 2000 m, however at depth the distribution of biogeochemical and anthropogenic perturbations variables often show a systematic bias toward underestimation. Therefore it is imperative for the scientific community to increase its understanding of deep-ocean transport and ventilation processes and assess their impact on the following biogeochemical processes:

- The amount of anthropogenic CO_2 stored in the deep ocean and rates of change,
- The sedimentation and burial of particulate carbon in the seafloor,
- The impact of changes in temperature, salinity, and currents in the deep ocean on biogeochemical parameters,
- The impact of increasing anthropogenic CO_2 in the deep ocean on biogeochemical parameters,
- The changes in ventilation and circulation to be assessed with transient tracers,
- The state and dynamics of oxygen consumption and availability including relative influences of biogeochemistry and advection.

To date an important conclusion of research and projects is that several of the semi-empirical approaches using observations and most modeling efforts, underestimate the penetration of the human-induced climate signals and associated anthropogenic carbon load into the deep ocean. Underestimation from observations can be attributed to the imprecision of the biogeochemical measurements coupled with the relatively small signal of CO_2, which leads to an a priori assumption that deep water does not contain anthropogenic carbon.

Transient tracers such as CFCs can be measured at relatively greater accuracy as they are not impacted by biogeochemical transformations which confound the interpretation of changes and trends in carbon content. However, the utility of these observations is limited by their atmospheric release history, which took place during the last approximately 60 years. Means to extrapolate the findings further back in time have been achieved by methods such as transit time distribution TTD (Khatiwala et al. 2009) but they are based on basic assumptions of transport in the ocean that cannot be validated. Furthermore, comparing CFC penetration results from numerical models compared to observations suggest the same bias of a lack of deep penetration witnessed in many models.

Each year the deep ocean is renewed with 2 petagrams of carbon exported as Dissolved Organic Matter (DOM), or about 20% of total export production. This exported DOM is only moderately reactive, such that it is remineralized to CO_2 at depth within a few decades. Little is known about how remineralization may change with time since so few observations exist, further it is expected that the export itself may be highly variable. The initial accumulation of exportable DOM in the surface ocean, and hence the amount of material available for export at overturn, is a function of surface ocean vertical stratification; the more stratified the system the more of this material that can accumulate. Furthermore, the biological utilization of DOM at the surface prior to deep-ocean export sets the liability spectrum of DOM exported to the deep-ocean. The turnover time of DOM at varying depths will affect carbon sequestration. In-situ measurements of DOM concentrations and turnover at in-situ temperature and pressure are required to extend understanding in this area. The actual export of DOM to depth is controlled by the strength of ocean circulation; the more water transported to depth the more DOM exported, and the deeper the ventilation and the longer the period for carbon sequestration at depth. As such, overturning dynamics at the ocean surface have a strong impact on the export of DOM; variability of DOM at depth is a direct reflection of the changes in the physical ocean at depth.

The flux of particulate organic carbon to the deep-ocean is a crucial parameter to understand given its role as the biological carbon pump for atmospheric CO_2 storage in the deep-ocean and as a resource supply to benthic environments. Particulate Organic Matter (POM) is the main source of energy to most deep-sea life, and - when buried in the seafloor- also represents a relevant carbon sink at geological time scales. This particulate organic carbon flux within the deep ocean represents an essential variable to detect changes in sedimentation and energy availability to the deep sea.

Globally Particulate Organic Carbon (POC) flux into the bathypelagic realm (>1 km) spans several orders of magnitude (1-605 mmol C m^{-2} yr^{-1}) and is characterized by important regional differences. In addition to general differences in magnitude there are also strong differences in the seasonality of POC flux. This varying degree and episodic nature of bathypelagic POM fluxes are likely to be important factors in the structuring of benthic communities and determining POC burial in sediments. There have been numerous long-term deep-ocean sediment trap deployment programs. An important finding from these deployments is that inter-annual variability can be equal to- or exceed, regional differences (Smith et al. 2013, Henson et al. 2015). Thus sustained regional observations appear necessary to characterize the spatial, seasonal and inter-annual variability in bathypelagic flux characteristics of a given site. Recent investigations show that the composition of the plankton in the productive surface layers, and the food-web structure, are important factors in defining the relationship between productivity and export flux (Ruhl et al. 2014, Soltwedel et al. 2016). The type of organisms producing and grazing on matter can significantly change the sizes and sinking speeds of particles.

The decrease of Particulate Organic Matter (POM) with depth is important for both CO_2 sequestration and providing an energy supply to the abyssal ocean. Deeper penetration of CO_2 from remineralized POM increases time-scales of sequestration and is dependent on vertical water mass structure and its ventilation dynamics. Remineralization of POM as it sinks through the water column modifies both the concentration and composition of carbon in sinking particles. In addition to magnitude and timing of POC arrival at the seafloor, the “quality” (composition) of POM appears to be relevant for structuring the biomass and turnover of deep-ocean fauna. Attenuation of POM with depth is fundamentally driven by particle settling velocities and remineralization rates. Both of these factors are dependent to some degree on surface and mesopelagic plankton and microbial communities. An important challenge for the future is to try and understand how POM inventories, fluxes and remineralization rates are distributed across different particle size classes. Following from this is the importance of developing an understanding of how climate-driven changes in the diversity and structure of surface ocean plankton communities might influence the diversity of benthic communities. Specifically to what extent changes in mesopelagic/bathypelagic particle structure and remineralization may buffer or accentuate the climate sensitivity of pelagic-benthic coupling. Particle distributions and fluxes, and their biological and chemical composition are needed to address these important goals.

Oxygen is fundamental to most of the life in the ocean, understanding the nature and causes of oxygen variation is necessary to predict biological responses to climate change. Ocean warming induced changes in solubility, stratification, ventilation, other wind-driven local hydrodynamic forces, and respiration are leading to global declines in ocean oxygenation, termed deoxygenation (Keeling et al. 2010). This is happening in the open ocean and on the coast and estuaries (Levin and Breitburg 2015). Oxygen is highly sensitive to changes in biomass and respiration; biogeochemical drivers interact with physical forcing to shape the oxyscape. Upwelling has intensified (Sydeman et al. 2014) and hypoxic areas have expanded at intermediate depths in some areas in the Atlantic and Pacific and not in others (Stramma et al. 2010, Wang et al. 2015). Circulation changes also drive regional oxygen loss (Bograd et al. 2015, Gilbert et al. 2010). Few long-term oxygen measurements exist for deep waters. Long-term observations are needed that document oxygen variability over seasonal to decadal time scales and the longer-term secular trends in the deep ocean. Geographic emphasis on regions undergoing major change (the expanding oxygen minimum zones, E. Pacific and southern Ocean) and other regions reaching oxygen thresholds that affect ecosystem services (e.g., for fisheries), will provide the mechanistic understanding needed to properly model future oxygen changes and biological responses.

Biodiversity and Ecosystem Observations

Many habitat changes on deep-sea margins are the result of destructive extraction activities [e.g., bottom trawling], however, increasing climate-induced changes in hydrographic properties (temperature, the carbonate system, and oxygen), circulation, and productivity will alter entire deep-pelagic and seabed ecosystems (Mora et al. 2013, Levin and Le Bris, 2015). Deep-ocean ecosystems perform key regulatory services (carbon burial and nutrient cycling), and supporting services (habitat, trophic support), as well as provisioning services that contribute food resources critical for the health and future of planet Earth (Ramirez-Llodra et al. 2011; Thurber et al. 2014). In addition, these environments provide a valuable source of energy and hold vast mineral, trace and rare element reserves. Deep-sea organisms (most yet to be discovered) hold the evolutionary novelty and genetic potential that provide a key to future adaptation by life in the ocean, and have begun to provide us with valuable marine genetic resources (MGR) of value as pharmaceuticals, enzymatic processes and exotic materials. Cancer treatments, artificial blood, CO_2 scrubbers, and novel armor are a few examples of the uses for MGR.

An initial global approach to the biogeographic classification of ocean life and to highlight the need for targeted and distributed ocean observation was articulated by in the report on Global Open Oceans and Deep Seabed (GOODs) published by the United Nations Educational, Cultural and Scientific Organization (UNESCO)-Intergovernmental Oceanographic Commission (IOC) and the International Union for Conservation of Nature (IUCN) (UNESCO, 2009; Watling et al. 2013).

Today it remains a critical future task to develop concepts for the observation and valuation of marine biodiversity and ecosystem services, and their integration into national accounting systems (COP10 strategies). This includes identification of Ecologically and Biologically Significant Areas (EBSAs) and the development of scientific and technical solutions relevant to environmental impact assessments in marine areas. These are required for the holistic environmental management of deep-sea ecosystems.

High Level Mandates

The societal mandate for observing biodiversity and other biological features in the deep ocean comes from a growing commitment to protect the ocean's biodiversity. This commitment appears in multiple intergovernmental legal instruments, from UNCLOS to the UN General Assembly Conventions and Sustainable Development Goals. A key agent is the Convention on Biological Diversity (CBD), signed in Rio by 150 nations in 1992. The CBD is an international treaty devoted to sustaining life on Earth for human well-being. A CBD sponsored strategic plan for marine and coastal biodiversity (2011-2020) focuses on the adverse impact of climate change on marine and coastal biodiversity (e.g., sea level rise, ocean acidification, coral bleaching), on the conservation of marine habitats through the establishment of Marine Protected Areas (MPA), and on the need for further research to investigate the role of the ocean and its ecosystems in the carbon cycle.

With regard to the deep ocean, the CBD proposes the careful management of deep-sea fisheries, consistent with precautionary approaches, and the establishment of impact assessments that further marine scientific research, and use the best scientific and technical information available to identify areas where vulnerable marine ecosystems are known or are likely to occur. Other elements of the UN biodiversity mandates that relate to the deep sea include the Regional Seas Conventions in national jurisdictions, as well as frameworks that go beyond national jurisdictions Convention on Migratory Species, CITES, and the Regional Fisheries Management Organizations, the International Seabed Authority (which has jurisdiction over the seafloor), the

International Maritime Organization, and the International Whaling Commission (Ardron et al. 2014). There is also a new UN treaty on biodiversity beyond national jurisdiction (BBNJ) that is in preparatory meetings this year (Wright et al. 2016). Together with Sustainable Development Goal 14, which advocates conservation and sustainable use of the ocean, these generate a mandate for observation of deep-sea biodiversity and ecosystems.

While the deep sea may seem a remote environment, far from the influence of humans, this is no longer the case. Human presence in the deep sea is growing exponentially with accumulating waste, increasingly deeper fish and shellfish harvesting, fishing gear impacts and bycatch, deepening oil and gas extraction, and new deep-sea mining activities (Ramirez-Llodra et al. 2011), (Mengerink et al. 2014). Despite its value as a wilderness area and as such a natural reserve for much of the planet's wildlife, in many societies today public acknowledgment of the detrimental human impact on the deep sea remains low.

Science Challenges

Biological response to changes in ocean environments may take many forms, on all levels from genes and metabolites to communities and ecosystems:

- Changes in species abundance (biomass/density), composition, diversity, with consequences for community structure and function and habitat ranges and distribution,
- Behavioral responses, after prey capture efficiency, bioturbation (avoidance, swimming efficiency, prey capture efficiency),
- Reproductive responses (spawning, dispersal, recruitment),
- Physiological responses (growth rates/timing, calcification rates, rates of chemoautotrophic CO_2 fixation, methane oxidation rates, respiration rates, growth efficiency, tolerances and thresholds),
- Evolutionary adaptation,
- Genetic responses (diversity, mutations, gene expression and products), and
- Trophic and other species interactions (prey availability, predation rate and symbioses).

Concluding in 2010, the Census of Marine Life, a decadal program established a baseline for life in the ocean. As part of the program there was a focus on different deep-sea realms, from margins- to deep-sea-basins and ridges, and from detritus-based-ecosystems, to chemosynthetic-based-ecosystems. Deep-sea biologists and geologists highlighted the great variety of benthic habitats along with their unique characteristics including species diversity, community composition, as well as the abundance and biomass of organisms; from bacteria to large fishes. The study also identified critical data gaps in observations, where knowledge is much needed including in the deep pelagic realm, the central ocean gyres, and the ice-covered polar oceans. Another critical gap lies in the temporal dimension and particularly short-term response to transient events.

The deep ocean is still the place of great discoveries, of new habitats, and new species. The number of species living in this remote environment remains a mystery, with estimates from 1-10 million for animals, and orders of magnitude more for microorganisms (Mora et al. 2011). Furthermore, it is suspected that species turnover on vertical and horizontal spatial scales, as well as on temporal scales, may also be as high as is seen in coastal and terrestrial habitats (Brandt et al. 2007; Zinger et al. 2011).

The evolutionary rates, adaptations to physical change and chemical stresses, and the role of deep-sea life in critical ecosystem functions such as remineralization, carbon sequestration, energy transfer, and precipitation of minerals is far from being understood. Single cell organisms like protozoa, bacteria, archaea and their viruses remain undiscovered or not described (e.g. Lecroq et al. 2011). Most of the pelagic realm remains unstudied (Webb et al. 2010). The behavior and domain of captivating deep-sea life like jellies and deep-sea sharks have not been well observed and documented. As almost all deep-sea animal life below 1000 m has in common is that it cannot be recovered while still alive, studies of their behavior and biology must be carried out in-situ or in high-pressure devices with limited time constraints. And while knowledge of remote environments has increased in the past decade, the vast majority of the ocean remains unsampled, and only very few deep-water observatories have been implemented (Glover et al. 2010).

The combination of exploratory and research-driven approaches towards observing under-sampled deep ocean ecosystems, and societal and climate-induced changes have generated a new imperative for studying, observing and understanding deep-sea ecosystems (Levin and Sibuet 2012). These studies have articulated the information most needed to assess, evaluate and predict future biological responses in the deep ocean. For example characterization of population connectivity (exchange of genes, larvae, and adults in space and time) is critical for evaluating ecosystem resilience and persistence in the face of disturbances such as mining, trawling, and hydrocarbon spills. Knowledge of what controls colonization and community succession can lead to greater understanding of resilience and guide remediation, mitigation, and restoration activities following both natural and human-induced disturbances.

The integration of major theoretical and conceptual frameworks in the development of deep-water observing goals and technological approaches is desirable (Levin and Dayton 2009). Some of the conceptual issues relevant to healthy roles and functional relationships of ecosystem engineers include the interactions of animals and microbes, predators and prey, parasite and facilitator, trophic web topology, productivity and diversity relationships, and population dispersal, connectivity and resilience. These basic scientific understandings are essential to establish concepts for the observation and protection of all levels of biodiversity (genetic, species, communities and ecosystems).

In addition to these conceptual frameworks, important scientific questions methodological tools and approaches as to the functioning of deep-sea ecosystems include: Do diverse and non-diverse systems respond similarly to perturbation, and do they differ in resilience? How can areas at risk for loss of biodiversity be detected? How can recovery from loss of biodiversity be detected? How can we reduce the threats to deep-sea biodiversity by implementing protected areas? How can we optimize the effectiveness protection measure under climate change influence? How will changes in temperature, oxygen, and CO_2 affect community stability and resilience? Quantifying the consequences of these responses for ecological/ecosystem functions (respiration rates, remineralization rates, biomass production, trophic pathways, nutrient fluxes, bioturbation rates, carbon burial rates) becomes a high priority if we are to manage the ocean sustainably. The above-mentioned parameters and processes are essential to select, implement and manage deep-sea marine protected areas, to develop ecosystem baselines against which environmental impacts are assessed, and to monitor change and even assess fiscal debt resulting from the loss of ecosystem services.

PART TWO

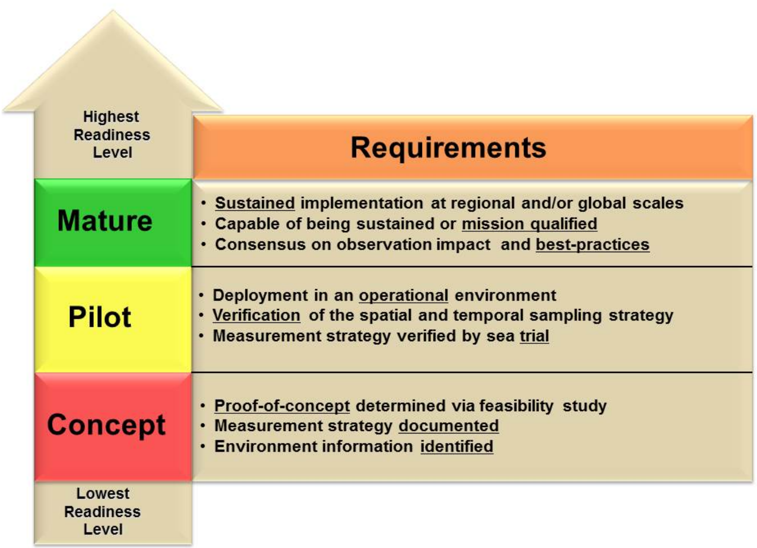
Requirements Setting: Proposed Essential Ocean Variables for the Deep Ocean

Introduction

The following section introduces a suite of draft EOVs for Deep Ocean Observing. EOVs can include both intrinsic and extrinsic properties as long as they address the overall GOOS Themes – Climate, Real-Time Services, and Ocean Health. The GOOS Framework suggests that EOVs must be capable of being observed or derived on a global scale, and must be technically feasible using proven, scientifically understood methods. Generating and archiving data on the variable must be affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

The deep-ocean EOVs recommended here build on and in some cases overlap with, the shallow water EOVs developed by the GOOS Framework (see http://goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114). However, many of the biodiversity and ecosystem EOVs developed for shallow water are not relevant for deep water. It is important to recognize that the status, maturity level, and ubiquity of EOV coverage may differ in shallow and deep water, depending on sensor depth ratings and accessibility. A table listing the Current GOOS EOVs and proposed DOOS EOVs as of December 2016 is provided in Appendix D.

These EOVs are presented as drafts. As the Strategy matures over time, these EOVs will be reviewed according to several criteria:



- Their contribution to scientific knowledge and/or societal issues,
- Their feasibility, maturity and sustainability (readiness) of the observing technology (refined by individual scientists, national programs, and international pilot projects),
- Their costs.

To justify a global observation, a requirement must be quite broadly accepted, and the need articulated at the international level. In order to justify an EOV observation over a sustained period, these requirements will need to be refined in a manner independent of specific technologies or implementation approach. Through this process and over time, stakeholder discussions on new requirements will take place in the context of existing observation elements; as any case for changing or creating a new requirement will include an evaluation of its added value. This report is intended to begin this iterative and adaptive process involving regular re-evaluation of deep-ocean EOVs constantly informed by new knowledge, technologies, issues, and priorities.

In the following section the requirements for Climate and Physical processes in the ocean are most mature, while the Carbon and Biogeochemistry, and the Ecosystem and Biodiversity requirements are less mature. For the Biodiversity and Ecosystem community the requirement-setting process is very much in the concept phase as limited in-situ observation of the deep-sea environment has taken place. This makes it difficult to fully articulate requirements that respond to science questions borne from repeat observation of baseline activities and changing conditions over time. It should be noted that the Southern Ocean Observing System (SOOS) in 2016 released its Report on the ecosystem EOVs in the Southern Ocean (Constable, et. al. Journal of Marine Science, 2016.) Much of the requirements set forth in this Draft Report are what will be required to witness, potentially for the first time, this little known arena of scientific exploration and discovery.

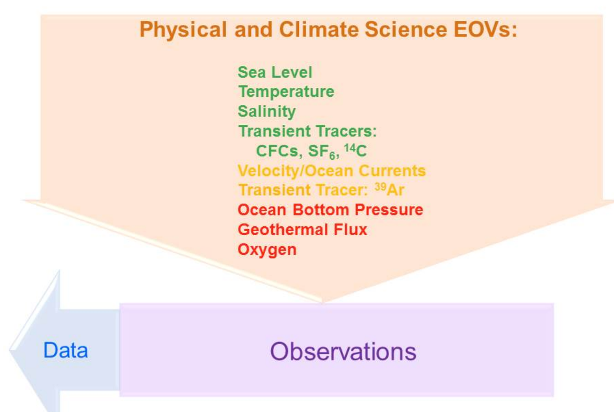
Climate and Physical EOVs

Mature Phase

Sea Level is inextricably linked to deep-ocean characteristics of temperature and salinity. As the deep ocean warms or freshens it expands, and contributes to sea level rise. In order to construct a sea level budget it is necessary to quantify the contribution of deep-ocean temperature and salinity variability to changes in sea level. Closing the sea level budget is needed for understanding changes and predicting future tendencies in sea level change (e.g., Wunsch et al. 2007).

Temperature in the deep ocean, in addition to its role in sea level, is also vital for quantifying the global energy imbalance. Within the climate system the oceans are the largest repository of the accumulated heat from man-made greenhouse gas increases, and the deep ocean plays a critical role in this storage system. Understanding how much and where, this heat is stored in the ocean is vital for the validation of climate models, and the ability to predict how much and how fast the Earth will warm in coming decades.

Salinity in addition to its role in sea level, is a vital variability in the understanding of changes in the deep MOC, and ocean-cryosphere interactions. The freshening of Antarctic Bottom Water in recent years is thought to originate at least in part from melting of glacial ice (e.g., Jacobs and Giulivi 2010), and may be contributing to a contraction of Antarctic Bottom Water in recent decades (e.g., Purkey and Johnson 2012).



Currents are intrinsically linked to atmospheric forcing as well as, water temperature, salinity, and sea level; through ocean density and pressure fields, which largely govern ocean currents. Ocean currents are vital for diagnosing changes in ocean circulation as well as the attendant changes in ocean heat, freshwater, and other water properties (carbon, oxygen, and nutrient), including the transport of pollutants (hydrocarbon spills, radioactivity, etc.) or larvae/alien species.

Transient Tracers are useful in quantifying ocean ventilation, formation rates, and identifying anthropogenic carbon uptake. For instance, CFC inventories from data collected by the WOCE Hydrographic Program quantified modern formation rates for Antarctic Bottom Water (Orsi et al. 2002) and North Atlantic Deep Water (LeBel et al. 2008), as well as their variability (Huhn et al. 2013). Ocean tracers have also proven very useful for validating the performance of climate models in the deep ocean. When located close to the seafloor, they can also help identify sources of subsurface fluids, and venting at places such as at hydrothermal vents, submarine volcanoes, and cold seeps.

> **Chlorofluorocarbon/Sulfur Hexafloride:** Currently most important transient tracers are CFC-11 and/or CFC-12 and SF_6.The different time histories of atmospheric concentrations of these tracers can be exploited to estimate the spectrum of age (time since ventilation at the sea surface) of interior

ocean waters (e.g. Waugh et al. 2003). This information has wide utility including reconstructing uptake of CO_2, estimating oxygen utilization rates, and testing global climate models (Talley et al. 2016). These anthropogenic gases enter the ocean through air-sea exchange, and do not have any considerable sinks in the ocean interior. Their transient input function provides a means to estimate transport time-scales and mixing patterns.

Tritium and Helium-3: A large pulse of tritium in the atmosphere followed the atomic bomb tests in the 1960's. Although tritium decays to ^3He on decadal time scales its oceanic signal is still useful to monitor; particularly the pair of Tritium and ^3He. Additionally, primordial ^3He is released at deep ocean ridges making it a unique tracer for deep ocean circulation within about 1000 km from the ridges.

Carbon-14: This is a radioactive carbon isotope that is commonly used for dating of organic matter on time scales of several thousand years. Nuclear bomb tests in the 1960's resulted in a large influx of atmospheric ^{14}C, this bomb signal can now be measured in intermediate and deep waters. This change in ^{14}C has provided information on ocean ventilation and the carbon cycle for several decades (McNichol et al. 2000).

Oxygen in addition to its biogeochemical importance is useful in diagnosing ocean circulation and water-mass formation changes. Deep and bottom waters, when formed are oxygenated and become oxygen-poor with increasing distance (and time) from their formation due to biological consumption. At the ocean surface, oxygen concentration is determined by primary production, mixing and consumption, at the seafloor it is influenced mostly by total community respiration, or by fluid venting (e.g. seeps, vents). Changes in oxygen concentration can reflect changes in deep and bottom water formation rates or circulation strength. While oxygen is routinely measured from ships (mature), making highly accurate measurements from autonomous platforms is still in the pilot stage.

Pilot Phase

Argon-39 is among a variety of transient tracers that can potentially be measured as they are often related to different intervals of ventilation periods. ^{39}Ar is a very powerful tracer for areas of the ocean with slower ventilation as it has a half-life of 269 years, making it an important tracer to measure in the future establishing temporal variations and changes in ocean ventilation and transport of water masses, ocean mixing and uptake of anthropogenic carbon on centennial timescales. Recent improvements in the measurement technology (i.e. Atom Trap Trace Analysis (ATTA)) will make this an increasingly feasible tracer for measurement.

Ocean Bottom Pressure (OBP) captures column-integrated mass changes, and where measured at sufficiently high frequency, enables the quantification of integrated ocean column variability (Quinn and Ponte 2012). OBP can be retrieved from time-varying space gravimetry (GRACE), and from bottom pressure sensors, but the former resolves only broad spatial scales, and the latter is vulnerable to sensor drift.

Concept Phase

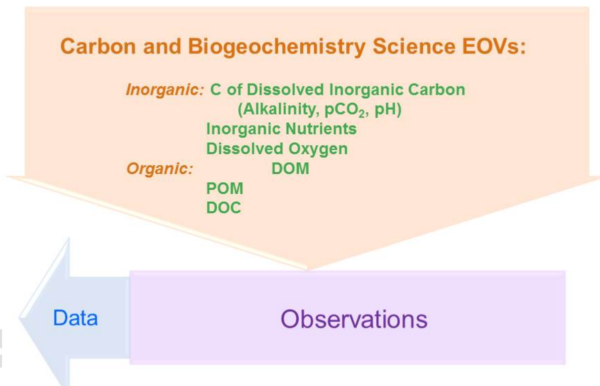
Geothermal Flux provides one of the bottom boundary conditions for the deep ocean. While globally averaged ocean floor heat fluxes of small (0.1 W m^{-2}), they do vary spatially with larger values at ocean ridge crests and smaller values on abyssal plains. The effects of ridge-crest plumes on ocean circulation can extend over great distances (e.g., Johnson and Talley 1997). Useful large-scale maps have been made from point measurements (e.g., Davies 2013), but smaller-scale maps might be of some utility.

Carbon and Biogeochemistry EOVs

Mature Phase

Inorganic Carbon is characterized by four measurable variables; total Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA), pH, and pCO_2. At least two of these variables have to be measured in order to fully characterize the state of the inorganic carbon system; including either DIC and/or TA since they can more readily be measured precisely and accurately through the use of certified reference materials. (Spectrophotometrically determined pH is a useful 3rd parameter because of the high measurement precision and growing interest in ocean acidification.) The inorganic carbon load in the ocean interior is roughly 50 times greater than that of the atmosphere. Further, as an increasing amount of the anthropogenic carbon reaches the deep ocean, absorption of this carbon by the ocean is an important process in quantifying the global carbon budget.

^{13}C of Dissolved Inorganic Carbon reflects the isotopic composition of atmospheric CO_2 that has changed due to human introduced excesses of CO_2 and is a bulk tracer of biological processes due to fractionation of carbon isotope during biological uptake. This modified carbon can be tracked within the ocean and provides important, and independent, information on the location of carbon in both in the contemporary and paleo-ocean (Quay et al. 2003).



Macro Inorganic Nutrients; Phosphate, Nitrate, and Silicate are important indicators of changes in water masses and biogeochemical activity, but also in human impact e.g. via eutrophication. Nutrient concentrations are an important parameter for observing changes in the biological pump and the location of anthropogenic carbon.

Dissolved Oxygen is a sensitive variable for monitoring changes in several ocean processes and water properties; these include warming, stratification, and biogeochemistry. The deoxygenation of water-mass needs to be monitored in order to assess ocean health and biological activity.

Dissolved and Particulate Organic Matter in the deep ocean is renewed each year by 20% of the total ocean export of Dissolved Organic Matter (DOM). Although the pool of DOM in the ocean is small in comparison to the inorganic pool, this carbon-enriched matter (greater than 200 times the carbon in living matter) has a large relative impact on carbon cycling in the ocean. The composition and age of DOM is relevant in determining the origin of water masses, their loading with terrestrial vs. marine materials, and the time of their transport in the global conveyer belt. DOM is a substrate for microorganisms, which can alter its composition and selectively transform DOM components. If microbes would be more efficient in degrading DOM, a higher flux of CO_2 into the atmosphere could be the result. New methods allow for the resolution of thousands of individual DOM compounds many of which remain unknown in their molecular structure.

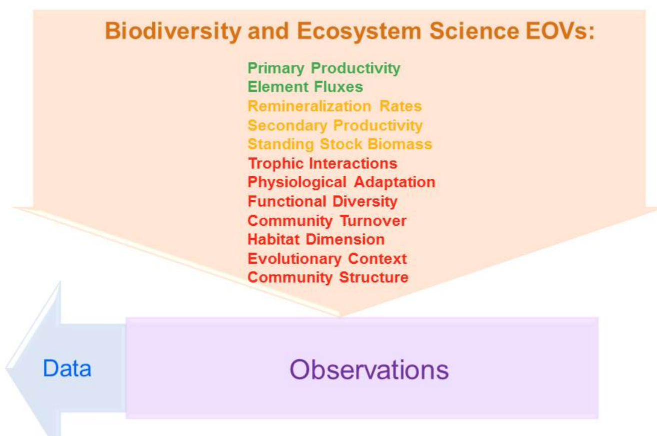
The particulate matter transported into the sea (aggregates, marine snow, fecal pellets) or produced by surface plankton is exported from the productive surface layer into the deep ocean where it forms the key energy source for heterotrophic deep sea life. POM fluxes can be measured by sediment traps autonomously at different water depths, as the composition of sinking particles allows estimates of the timing and community structure of phytoplankton blooms and their grazers. Sediment traps connected to oceanographic moorings remain a key tool in linking carbon fluxes to biodiversity and the food web structure, as well as to monitoring surface ocean and seafloor processes. Besides sediment traps, ocean seafloor community respiration via in-situ measurements is another robust method to assess POM fluxes. Optical methods for assessing flux quantities and character including size- and type-distributions are now evolving that show great promise for augmenting conventional approaches.

Biodiversity and Ecosystem EOVs

Mature Phase

Primary Productivity, or Chlorophyll, Ocean Color, Surface Productivity is as high as terrestrial productivity, and shows similar dynamics in space and time. Within the ocean primary productivity is restricted to the top 20-100 m and can be observed remotely from satellites, (by assessing chlorophyll, light availability and photosynthetic efficiency of the primary producers). It can also be assessed based on nutrient composition, and process measurements such as the uptake of $^{14}CO_2$. While not generated in the deep ocean, primary productivity is an important variable in the definition of biogeochemical ocean realms, from surface to depth and reflects the food supply to deep-ocean ecosystems, thus it is included here.

Element Fluxes, including vertical export of particulate and dissolved organic matter are major sources of carbon and associated bioelements (e.g. nitrogen, phosphorus, silicon, iron, etc.) to the deep sea. The biological pump describes the collective set of processes that result in the net export of organic matter from the upper ocean and subsequent selective remineralization of this material at depth. These processes are regulators of air-sea carbon exchange and ultimately act as key determinants on the partial pressure of atmospheric carbon dioxide. The biological pump maintains vertical gradients in these bioelements and results in the downward movement of elements against the vertical concentration gradient (hence the "pumping"). Moreover, the downward movement of organic matter from the upper ocean to the deep sea constitutes the major source of energy and nutrition for deep sea organisms. Organic matter can be exported from the upper ocean in both particulate and dissolved phases; globally these processes account for 15-20 GtC yr^{-1}. Export of particulate matter can be measured through use of sediment traps that capture downward settling particles, or through various geochemical approaches including ^{234}Thorium disequilibrium and elemental mass balances.



Pilot Phase

Remineralization Rates: Biochemical oxygen demand or total community respiration is the amount of dissolved oxygen consumed by organisms in a volume of water or sediment. It measures what is required to break down organic material measured at a certain temperature over a specific period of time. This variable correlates to carbon and energy availability, as well as to CO_2 flux and nutrient remineralization (via the Redfield ratio). In most deep-sea environments, the majority of oxygen consumption comes from microbial respiration, but deep-sea fauna and chemical oxidation of reduced compounds can also contribute significantly; such as at cold seeps and hydrothermal vents.

Secondary Productivity, or in-situ productivity generation time, is the rate of biomass formation or energy conversion by organisms such as grazers and decomposers. Due to the absence of light, primary productivity in the deep sea is restricted to areas where the availability of reduced, energy-rich compounds such as hydrogen, methane, sulfide, ammonium or FeII is high enough to drive bacterial or archaeal autotrophic CO_2 fixation.

At the sub-surface productivity is determined by the number of trophic levels and the lengths of the food chains within an ecosystem. Secondary production divided by total biomass of a group of organisms provides an estimate of their generation time. Bacterial secondary production is assessed by process rate measurements along with tracers of radioactive or stable isotope-labeled organic molecules.

Standing Stock Biomass in the deep sea, abundance of biomass, and the distribution of all organism size classes is generally a function of food supply and temperature within a particular habitat. Hence, standing stock biomass has been used as a proxy for energy and carbon flow to an ecosystem. Generally, the relative proportion of biomass decreases from small, single cell life -- which usually makes up greater than 90% of the biomass, to large megafauna, including fish -- which comprise less than 5% of the total benthic community biomass. This is assessed by counting organisms across all size classes, using microscopy or flow cytometry for small single cells, nets, continuous plankton recorders and acoustics, sorting and visual counting for small multicellular organisms, or cameras and acoustics (passive and active) for larger organisms.

Mesopelagic fishes are routinely monitored through a number of ichthyoplankton survey programs. The larval phase of most mesopelagic fishes is found in the upper 200 m of the water column and can therefore be quantitatively sampled by routine plankton sampling programs. The abundance of larval fishes provides an index of the abundance of the deeper adult spawning stock.

Concept Phase

Trophic Interactions: Food-web characteristics such as trophic levels and interactions are important functions of ecosystems as they are sensitive to changes, such as the removal of large predators by overfishing. Critical elements used to assess trophic interactions include stable Carbon and Nitrate isotope signatures (bulk and compound-specific), lipid biomarkers, and the accumulation of pollutants or tracers.

Physiological Adaptation: For some drivers of ecosystem change, it is relevant to assess potential niches of organisms and limits to their dispersal -- such as their physiological ability to adapt to temperature, pH, CO_2 levels, oxygen depletion, and pollution to name a few.

Taxonomic Diversity: The alpha diversity or the barcoding of organisms or species richness within a given habitat area is an important ecological variable. It can be assessed through the sampling of different size classes and genetic barcode analysis, or morphological identification. eDNA and high throughput genomics is starting to allow detailed quantification of even the smallest eukaryotes and prokaryotes. Development of these tools will greatly increase the space and time scale of measurements that can be obtained.

Functional Diversity attributes can be evaluated through biological trait analysis, and especially for microbes, through transcriptomics, proteomics and metabolomics including coral microbiomes and symbiont population of deep-sea invertebrates. A key goal in documenting change or recovery in the face of societal pressures (spills, trawling mining) is to understand the consequences for ecosystem function and ultimately ecosystem services.

Community Turnover: Beta-diversity refers to the change in species composition among geographic areas and is another important ecological variable which is required to understand natural and man-made-variations in community diversity, structure, and composition. An important parameter of beta-diversity is the spatial or temporal replacement of species, also known as community turnover. As with species richness estimates, the underlying measurements are species inventories, which are now often assessed by high throughput genetic sequencing.

Habitat Dimensions: The sizes and heterogeneity of habitats which are occupied by distinct communities are also important ecological features. Underlying measurements used to understand these environments include bathymetric maps, habitat mosaics, time-lapse photography, and landscape-scale imaging and chemical gradients mapping at different scales. The combination of environmental information and biodiversity assessments, along with geographic information systems are used to inform our understanding of ecological variations at various landscape scales.

Evolutionary Processes: Where and when species evolve has consequences for both the characteristics and functional traits of organisms. The ecological processes we observe in the present have been influenced by evolution. The evolutionary history of ecosystems and their communities is relevant to the assessment of potential for adaption, and species resilience to natural and man-made climatic variations.

Community Structure: The presence (or absence) of certain taxa, and their relative contribution to total abundance of organisms are essential variables to assess community structure. For microorganisms, DNA fingerprinting approaches, which compare sequence abundance, have been a way to accelerate the assessment of biodiversity variables such as taxonomic richness and relative composition. For animals, such estimates rely mostly on manual extraction of organisms from water or sediments, often by sieving (sediments) or filtration (water) according to size classes, and taxa identification and quantification by microscopy. New high throughput molecular methods (eDNA) may start to be developed for smaller taxa but will require comparison with morphological approaches. For fragile gelatinous organisms, image-based survey techniques are often used. From abundance and wet weight or carbon mass, other important variables are derived such as biomass, production; or estimated species richness, species turnover, and taxa- area relationships.

PART THREE

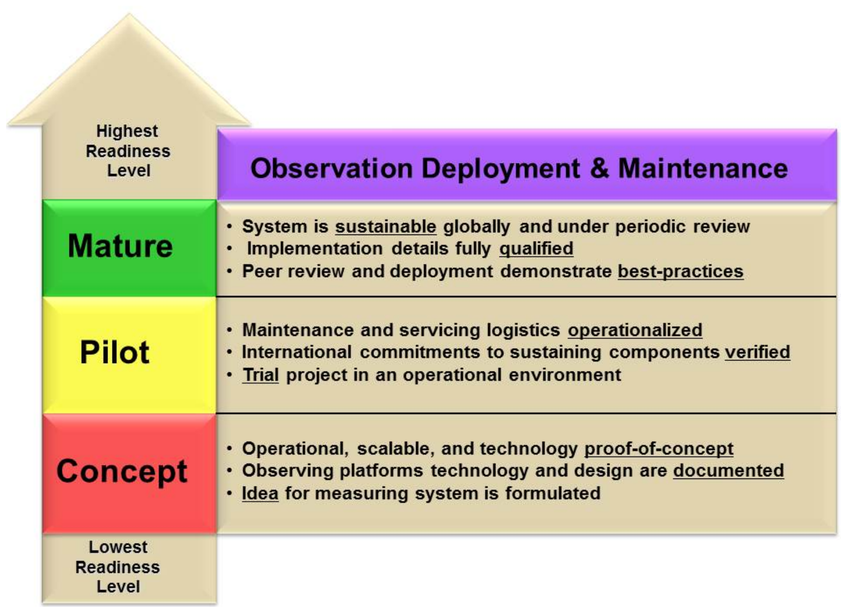
Deployment and Maintenance: Observing Platforms and Technologies Addressing the EOVs

Introduction

Ocean observing technology deployment and innovation are core processes of deep-ocean observing. Within the global ocean observing system it is the observation deployment and maintenance elements which connect the requirements to the need for technology and techniques which provide the requisite data needed by the user community in order to measure an EOV. Assessment of the readiness level of technologies aligned with an EOV, or EOVs, is the mechanism through which feasibility and impact of proposals for new or upgraded observation elements is assessed. Discussions focus on the adequacy of technology or measurement technique to meet the needs of a specific EOV.

Some elements of the deep-ocean physical, chemical, geological, biological and ecological observing system are already implemented. Presently critical components of deep-sea EOV assessment require quantification involving complicated shipboard measurements and ocean processes.

Ship-based measurement programs are a crucial component of the global deep ocean observing system. They provide very accurate reference data on ocean variables such as tracers, nutrients, the carbon system as well as biological parameters that cannot yet be quantified via any other means (e.g. Talley et al. 2016). However, expanding ship-based measurement programs to adequate spatial sampling and sufficient observations to resolve seasonal and shorter, time-scales over the globe would be prohibitively expensive; given the high cost of ships, fuel, and people. Hence, these ship-based observations need to be combined with permanent fixed point observatories and moored arrays designed to provide measurements of temporal change, and arrays of autonomous platforms (e.g. floats and gliders) designed for global, year-round coverage that will inform future ocean climate, physics, and ecosystem studies. Deep floats have been designed and are being tested in pilot mode and refined. An emerging field of design and deployment for fixed-point observatories is in the arena of cabled observatories capable of providing the power and communication bandwidth required for sustained and potentially dynamic long-term observations of deep-sea environments. Acoustic methods continue to evolve to remotely sample the ocean between fixed (or moving) platforms, e.g., acoustic thermometry and tomography, that can also provide long-range navigation signals for floats (OceanObs'09 Dushaw white paper). Expanding our understanding of climatic vulnerability of seafloor ecosystems and related functions (including climate-related ones) will require monitoring of environmental variability and dynamic ecosystem responses using seafloor platforms.



Programs, Platforms, Networks

Below is a brief review of concerted deployments of deep-sea observing technologies. Often these programs, platforms, and networks are deployed to conduct geospatial or variable-specific studies. As such their deployment and operational maturity varies relative to their fit-for-purpose in the global sustained observing system.

In the following section technology readiness levels are assessed based on their scalability, maintainability, and documented best-practices for predictable deployment and use. So, while it may appear that some technologies which have been successfully deployed in highly specialized environments may be listed as less mature, this is due to the fact that they have yet to be fully vetted at a scale required to meet the global measurement needs of a globally sustained EOV observing system.

Mature

Shipboard Surveys: Deep-sea, reference quality, measurements of climate, biogeochemical, and biological variables are mostly taken during shipboard surveys, and their results submitted to data repositories. Vital for the assessment of climatic variations are the repeat section studies conducted as part of the GO-SHIP Program. Presently, the GO-SHIP program supports a limited number of trans-oceanic studies typically repeated at decadal intervals (Talley et al. 2016). This sparse temporal sampling with large gaps between ship-tracks (typically a few thousand kilometers) results in incremental increases in the understanding of the global deep ocean at decadal and longer time scales. As a result efforts to completely quantify sea level, energy and freshwater storage, are hindered by large uncertainties. The physical and climate and biogeochemistry communities coordinate well and data collection policies of these activities are mature. However, for biological surveys, global and cross-regional coordination of sampling efforts are still rare, and need a high level of standardization of sampling equipment, data, and metadata. Mobile laboratories composed of arrays of small autonomous benthic platforms (associated or not with fixed point observatories) will be needed to address specific climate-sensitivity within regions of particular interest/concern across relevant and common spatial scales.

Shipboard Time Series: There are several deep-sea locations that host ship-based studies of time series of sea floor biological communities and processes (Glover et al. 2010; Smith et al 2013). At abyssal depths time series studies have been conducted in several of the world's ocean basins. Most of the time series that began in the 1940s with the ocean weather ships have been discontinued, but others are still visited frequently. A few monthly visited stations have been instituted near mid-ocean islands (e.g., HOTS and BATS). During this time, spanning a range of depths and environments, nearly all of the studies have witnessed changes in both hydrographic properties along with corresponding biological responses (Glover et al. 2010).

Mooring Arrays: There exists a limited suite of mooring arrays designed to observe a range of regions and deep-ocean phenomena. These moorings provide valuable measurements of deep-ocean variables such as temperature, salinity, and currents at high temporal resolution (compared to ship-based measurements), but lack comprehensive spatial coverage. In the future specially equipped moorings with bio-optical and biogeochemical sensor modules, sediment traps and/or camera systems are key to link physical and chemical variations to biological ones; and surface ocean processes to those in deep ocean and seafloor realms. A promising development, the international network OceanSITES is improving its measurement of the deep ocean by deploying mature temperature and salinity sensors on their moorings below 2000 meters.

Remotely Operated Vehicles, Manned Submersibles, and Submersibles: Over the past few decades several long-term studies of geochemistry and biological structures have been conducted at different types of hot spot ecosystems such as cold seeps, cold water coral reefs, deep-sea hydrothermal vents, or seafloor experiments (e.g. LTER site Hausgarten). A variety of submersibles and Remotely Operated Vehicles (ROV) have been used to study and conduct experiments in a variety of communities associated with whale falls, seep benthos, canyons, hydrothermal vents, and deep-ocean ridges. However, the long-term study of midwater ecosystems offshore Monterey is the only one of its kind, in a habitat the makes up most of the oceans volume. Completely lacking are time-series data from depths of 6,000-11,000 meters in the ocean's trenches.

Pilot Phase

Autonomous Single Moorings and Mooring Arrays: Other techniques including sustained autonomous moorings and mooring arrays are presently sampling throughout the water column at a variety of key locations (e.g. OceanSITES, review by Glover et al. 2010). However, autonomous mooring technology must be improved in order to allow for more long-term and deeper measurements. Instrument development is essential in order to permit operation at variable depths (profiling of subsurface and surface), increase the lifetimes of mooring deployments including their energy supply, improve the stability and accuracy of instrument calibrations, decrease the cost of hardware and deployments, and allow continuous or occasional telemetry of data to shore. Data telemetry in ice-covered and particularly harsh environments requires development of retractable mooring components (i.e., underwater winches) and automated detection of ice cover and sea state. Despite the benefits offered through the expanded use of moorings and arrays, cost and logistic considerations preclude global deployment at sufficient spatial resolution required to quantify global heat and freshwater inventories, and changes in global circulation patterns.

Deep Floats and Gliders, Long Range AUVs: In order to achieve adequate global sampling of the deep ocean some combination of deep floats and deep gliders must be deployed. Both deep floats and deep gliders are extensions of existing technology, and are being matured to include the measurement of temperature, salinity, and soon oxygen, along with other water properties such as nutrients or gases. Sensor technologies are being developed that are sufficiently long-lived, small, efficient, and affordable. Gliders can also measure velocities directly using ADCPs. Deep floats offer the possibility to extend some EOV measurements from 2000 m to full ocean depth. Indeed, several nations are currently deploying small numbers of deep Argo floats in pilot regional arrays, with a design study for a global Deep Argo array (Johnson et al. 2015). Repeat glider tracks could be established and designed to increase the temporal and spatial resolution of shipboard surveys. The deployment of some combination of autonomous assets is appropriate, with deep gliders repeatedly measuring across strong and variable boundary currents, while deep floats measure the broad interior.

Cabled Underwater Observatories: Recently, permanent cabled underwater observatories have offered a unique step forward in fixed-point ocean observation. Their ability to measure a broad range of environmental elements is enhanced by their dedicated power and communication capabilities. Deep-water cables provide energy and communication enabling repeat, temporally and spatially targeted biological sampling and analysis in both the water column and at the seafloor. Sensor sampling can also be coupled with video- and photographic recording of habitats, organisms and processes. These observatories have the capacity to provide new measurements for all fields of ocean science, especially energy- and data-costly camera observations; to integrate those which have not been covered by autonomous sensing, including derived processes, such as productivity, growth rates, and biodiversity shifts. Modular instruments for bio-optical, molecular, chemical, genetic and behavioral studies exist, but can only be deployed in the open ocean for research when accompanied by an energy source and data transfer capability. Therefore substantial innovations are to be expected through the use of cabled observatories, especially in the fields of biological oceanography and ecology, and monitoring biodiversity change and ecosystem function.

Over the last two decades, various flavors of undersea cables systems for ocean observing have been installed and are operating. Single node systems such as MARS (Monterey Bay at 900 m) and the ALOHA Cabled Observatory (ACO at Station ALOHA, the site of the Hawaii Ocean Time series) can provide a fair amount of power and communications in a plug and play fashion. Regional scale systems with multiple nodes over 100s of kilometers are represented by NEPTUNE Canada, DONET, and OOI cabled array. DONET also functions as a seismic/tsunami early warning system. The S-Net system off Japan is strictly an operational warning system (5000 km, 200 sensors), albeit its pressure sensors would be very useful for oceanographic use.

Beyond the wide range of sensors and instruments that can be deployed via a broadband cabled observatory, they may have the capacity to host a series of data-intensive technologies such as robotics, video, and in-situ molecular measurement techniques. Sporadic events once detected, with the aid of network technology, may allow researchers to interact with the modular components of the observatory and potentially adapt the sampling patterns of individual sensors to dynamically add observations and manipulations. This opportunity will enable custom observation and research of episodic events such as sudden hydrocarbon releases, volcanic eruptions, ocean temperature anomalies, and severe benthic storms. Observatories focused on the seafloor will offer earth and ocean scientists new opportunities to study multiple, interrelated processes over time scales ranging from seconds to decades. These include episodic processes such as sporadic deep-ocean convection at high latitudes, submarine slides, along with the resulting biological, chemical and physical changes. Additionally, these observatories will allow for the study of processes taking place over periods ranging from months to several years, such as methane hydrate dissolution, biomass variability, as well as global and long-term changes including warming trends and ocean acidification.

Concept

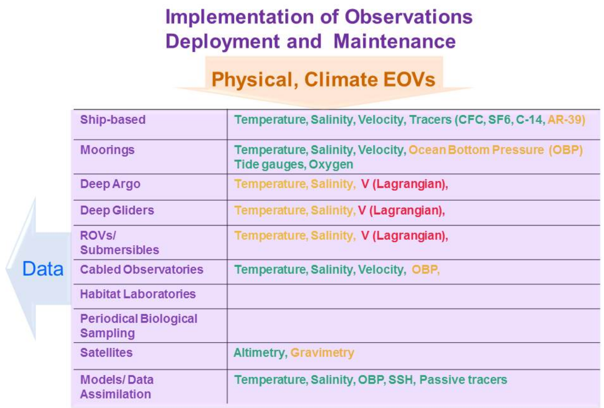
Mobile Deep-sea Laboratories: An approach championed by benthic researchers and the deep-subsurface microbiological community has been the development of mobile deep-sea laboratories, which may be moved from region to region. These mobile facilities are frames (landers) capable of hosting a suite of hydrographic, biogeochemical, optical and acoustic sensors, as well as fixed biological survey equipment (e.g. benthic chambers, microprofilers, sediment traps, plankton recorders, larval pumps, molecular sequencers) and process experiments (e.g., respirometers, colonization substrates, organic falls). These facilities offer the option of deployment and operation in different regions for extended periods of time (months to years), as well as being replicated and deployed in multiple deep-ocean settings. Once mature the community may elect to support an international manned habitat in the deep sea.

Environmental sensing on telecommunications cables: At the concept phase is a new effort to add environmental sensors to trans-oceanic commercial telecommunications cable systems (JTF SMART Cables, http://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx). These systems have repeaters every 50-100 km (e.g., mesoscale resolving along the cable path), which can provide modest power and communications. Current plans call for ocean bottom pressure and temperature, with 3-d acceleration, to monitor ocean circulation and climate, tsunamis and earthquakes. Given that there are about 1.5 Gm of presently installed cable (with 25 year life), and it is refreshed every 10-15 years for new technology, over this same time frame one could obtain as many as 20,000 seafloor mini-nodes spanning ocean basins. It is likely that additional/other sensors (e.g., salinity, passive acoustics, inverted echo sounder/acoustic modem, bio-optics, among others) could be added. This new application riding “piggy-back” on existing very mature, extremely high reliability technology can provide a very robust complement to the current in situ and satellite sensing (altimetry and gravity). (https://eos.org/meeting-reports/submarine-cable-systems-for-future-societal-needs).

Sensors, Processes and Techniques

For the deep ocean observing community obstacles related to the advance of deep-sea observations include the limited suite of sensors, analytical tools, or sampling instruments that can be deployed on autonomous platforms. Processing and analyzing data streams like those from photographic or genetic sequencing is highly effort intensive. Such analytical workflows will benefit from continued development towards removing human intervention steps in generating useful knowledge. Today, time series studies of the deep ocean depend primarily on ship-based sampling efforts (Glover et al. 2010) that are expensive and difficult to sustain at temporal and spatial scales required for climate studies. As such the deep ocean observing community is challenged to expand the observing system and determine the appropriate mix of existing sensors and platforms and the attendant deployment of new fixed and autonomous sensors and platforms.

Several elements not traditionally incorporated into observing systems may be considered:



- Visual: Video and photo camera imagery, Repeat large-scale AUV (image) surveys of the bottom for biology
- Sediment profile imaging camera
- Acoustics: Sonar, passive monitoring, ADCPs, inverted echosounders, long-range navigation and acoustic tomography/thermometry
- Optical instrumentation: particle counters, Zooscan
- Time series: via surface ship (e.g., coring, landers), ROV, HOV, hybrid vehicles (sampling and transects of various sorts - cores, hard substrates, biogenic substrates) and geochemical tracer applied to ecological studies
- In-situ samplers: Plankton recorders (gauze), Larval pumps, Sediment traps, fluid osmo-samplers
- Experiments: respirometers, carbonate dissolution units, tracer deployments, colonization substrates, sediment manipulations, organic enrichments (carcasses, phytodetritus)
- In-situ Molecular/Genomic analysis, and new autonomous chemical sensors O_2, H_2S, NO_3-, CO_2/pH, N_20) for experiment monitoring
- Horizontal electric field to determine absolute barotropic velocity, using cables, “point” sensors on the bottom, and floats

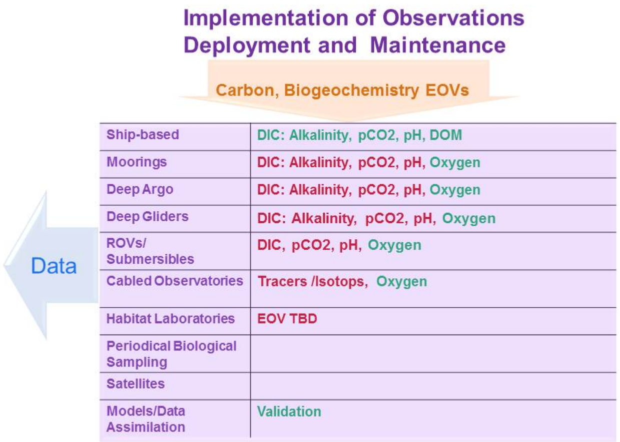
Physical and Climate Observations

Sensors that measure temperature, salinity, tracers, and velocity on platforms such as ships, moorings, and cabled observatories are relatively mature. Sampling of CFCs, SF_6, can be measured with a high degree of accuracy and precision from seagoing research vessels and analyzed on board, while ^{39}Ar sampling requires that the samples are stored during the cruise for later analysis on shore, (IOCCP report 14). Additionally, ^{14}C measurement techniques are well established, and completed on-shore once the cruise has completed.

Temperature and salinity measurement technologies on deep Argo floats, gliders, and submersibles are currently being tested and matured. Ocean Bottom Pressure (OBP) measurements on moorings, on cabled observatories, and gravimetry on satellite platforms are also being matured.
In situ measurement of currents on moored arrays is mature, but is in the pilot phase with regards to the deployment and use of deep gliders and deep Argo floats. Another emerging practice is the combination of OBP and sea level measurements at sufficient accuracy levels as to enable the distinction of where and what changes in mass and heat content impact sea level (Ponte 2012).

Acoustic navigation and tomography are used to better define the ocean velocity field, acoustic float tracking has long been used for process experiments. One should consider the implementation of basin scale infrastructure systems (i.e., sources at lower frequency, broader bandwidth) to affect this, using receivers on Argo floats (“shallow” and “deep”) as well as conventional deep RAFOS floats. This would enable obtaining long term, high temporal resolution trajectories (velocity EOV). The same acoustic receiver can be used for wind and rain measurements (EOVs?), marine mammal and “soundscape” monitoring (EOV?).

Acoustic tomography is technically mature, having been used in cabled (ATOC) and moored scenarios for decades. Arrays are currently deployed in Fram Strait and the Beaufort Sea with expansion into the Arctic anticipated (led by Norway). Water column spanning temperature and absolute velocity (EOVs) with some depth resolution can be obtained from the acoustic travel times between instruments. Work is underway to use mobile platforms as receivers (e.g., gliders). The same low frequency broadband sources could be used for both navigation as well as tomography. The path averages inherently suppress internal wave effects resulting



in a high signal to noise ratio. The method is calibration free (a time measurement). A very significant benefit of the method is the growth in the number of data is quadratic: think of n passive receivers on a SMART cable traversing an ocean basin. Adding a single source immediately gives n data; a second source adds another n data, and one could obtain high accuracy basin scale heat content in a day.

Carbon and Biogeochemistry Observations

In the carbon, biogeochemistry arena ship-based observations of inorganic carbon: alkalinity, pCO_2, pH are in the mature phase, while these same measurement technologies are currently in the concept or pilot phase when deployed on moorings, deep Argo floats, deep gliders and submersibles. Oxygen sensors are mature on ships, with accuracy and long-term stability close to being robust for floats and gliders. There is a continuing need to develop sensors that can be supported on autonomous platforms/robotics, as we need many more observations than can be made from ships, and the costs are orders of magnitude less.

The analytical methods for inorganic carbon samples are well developed. Certified reference materials are available, (for DIC and TA) and used to meet long-term accuracy requirements (Dickson et al. 2007 and Wang et al. 2007). In the future, improvements in sensor technology and data delivery times will likely allow for long-term, better calibrated, measurements of carbonate variables on autonomous platforms. These elements if present in the deep ocean interior, will be useful to monitor short time variability and seasonality, however, they will likely not be accurate enough to monitor decadal changes.

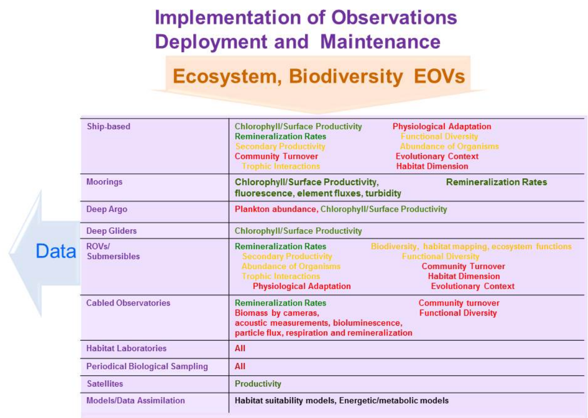
Total Dissolved Inorganic Carbon and $^{13}CO_2$ measurement and analytic techniques are well established, as well as ^{14}C using accelerator mass spectrometry (AMS). Samples are typically taken on the ship for shore-based analysis. These calibration routines and inter-laboratory comparisons are well established; in part as the result of extensive atmospheric $^{13}CO_2$ measurement intercomparisons.

To date, the accuracy of inorganic nutrient measurements have, in general, been insufficient in to quantify changes in the deep ocean. Measurements are normally done with spectrophotometric methods using auto analyzers. Analysis should be performed on the ship as soon as possible after sampling. Often preserving the samples for measurement on shore, after the cruise, has a negative impact on precision and accuracy. Certified reference materials are now available which will greatly improve accuracy and comparability of measurements as has occurred with standard use of CRMs for total dissolved inorganic carbon and alkalinity, and strongly recommended for use (IOCCP report 14; Gordon et al. 1993).

Dissolved Oxygen Measurements onboard are carried out using Winkler-titration, a technique established in the end of the 19^{th} century. Oxygen can also be measured precisely with sensors mounted either on the Conductivity, Temperature, Depth (CTD) package or on autonomous vehicles (gliders, floats etc.), however these measurements also require calibration and referencing using Winkler titrations (IOCCP report 14). A major advance has been the capability to reference the oxygen sensors to air and profiling floats are being reconfigured to offer this standardization each time it reaches the surface (Bushinsky et al., 2016)

Optical tools that include *chl-a* fluorescence, optical backscatter, holography and light-field imaging can be used in profiling modes to determine the particle type-and size-distributions in time or space (e.g. Briggs et al.

2011). Quantitative inferences can then be made for quantities like particulate organic remineralization length scale (RLS) (Sensue, Buesseler and Boyd 2009) or the types and sizes of particles associated with variation in RLS.



Biodiversity and Ecosystem Observations

Biological Oxygen Demand or Remineralization Rate observation techniques are in the pilot to mature phase across platforms. Oxygen consumption can be assessed by bottle or sediment core incubations and in-situ by chamber incubations or microprofiler measurements.

Standing stock or biomass distribution across taxa and faunal size classes help to assess trophic structure of food-webs. Some taxa and productivity can be assessed through the monitoring of bio-optical instrumentation, bioluminescence or by sound collected via passive or active hydro-acoustic measurements (for mammals, fish and zooplankton). The use of stereoscopic imaging, holography and light-field cameras not only shows promise for the quantification of fragile marine snow particles, but also important ecological quantities like gelatinous zooplankton that are very challenging to study otherwise. These measurements and spatial-temporal distribution requires additional experimentation and understanding.

There are several biodiversity and ecosystem EOVs still in the concept phase. The difficulty in capturing and observing deep-sea life presents tremendous challenges, although ship-based sampling methods are well established. However, expense, the high level of effort required, workflow / delay and invasiveness make them unsuited for routine and frequent observations at large spatial scales. LOKI, flow cytometry, and various optical imaging systems are well established. While these imaging systems are mature, the automated species recognition technology is not, and work is needed to enhance value for biodiversity assessment.

Trophic interactions can be observed through the study of stable carbon, nitrogen, sulfur isotope signatures, lipid biomarkers, and the accumulation of pollutants or tracers found in harvested species or those captured in traps. Physiological dispersion, and adaption to ecosystem change is commonly assessed through in-situ, shipboard or laboratory experiments, however, few deep-sea organisms are accessible.

Diversity baseline and turnover studies are difficult, again due to the challenges associated with observation and sampling. There has been some progress in gene-based rapid biodiversity assessments (e.g., metagenomics, DNA-barcoding), but successful application depends on baseline knowledge of species identity. Diversity indicators, such as rare versus abundant species, can be applied to estimate the proportional population of organisms. Diversity indices can also be used to assess resilience to change, along with the restoration of communities in impacted environments. More research may reveal indicators species that can be used (like a canary in a coal mine) to reflect the status and health of different ecosystems and provide early warning of impending change. However, the difficulty to validate biotic quality indexes will be as high as in the coastal zone.

The availability of an open-access repository for deep-sea genetic sequence data takes on increasing importance as barcoding and other genetic tools gain use in diversity assessment. This is particularly true for meiofauna, for which assessments are even more time consuming and require rare expertise.

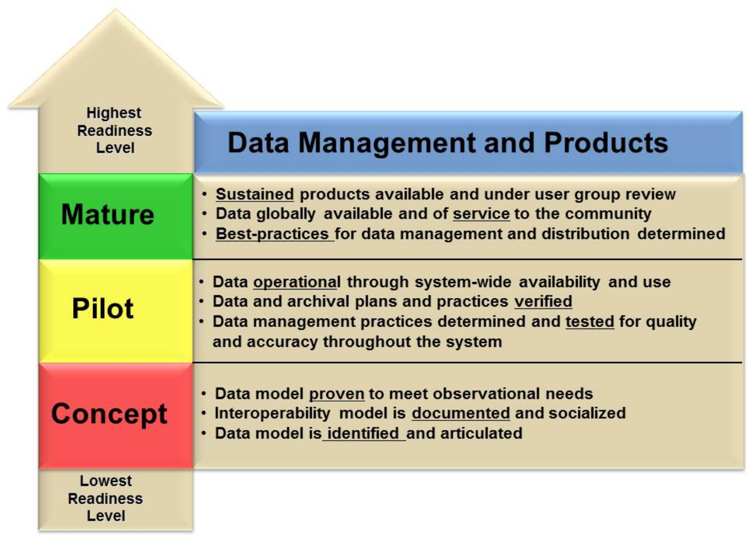
PART FOUR

Data and Information Systems

Introduction

As the output of the Deep Ocean, or any observing system, data and information products are the interface for most users. For the Deep Ocean Observing community, these products include raw data, derived data products, models, and software. We include all of these as “information products” that the DOOS information management strategy must address, and use the terms data and information interchangeably.

The need for data and information runs throughout the scientific goals of the Deep Ocean Observing System. A global understanding of the deep ocean, whether from the perspective of deep-water formation patterns, heat budgets, acidification, or biodiversity patterns, requires the integration of data from many observatories and research programs. Progress in areas like climate change, where forensic challenges to scientific results are likely, require that data, models, and model output be well-documented, citable, and of known provenance. Across the board, observations in the deep ocean are sufficiently sparse and expensive that available data should be shared and reused for the field to progress.



Information System Guidelines

As has been adopted by GOOS, the goal of the DOOS information management strategy and policy will be to foster an open and interoperable system of regional, coastal, and global observing networks that rapidly and systematically acquire and disseminate data and data products to serve the needs of scientists, government agencies, educators, non-governmental organizations, and the public. This document deliberately does not put forward a proposed architecture or technical framework for a DOOS information system approach, because the technical solution must follow the scientific requirements: as DOOS further develops the science components of its strategic roadmap, and conducts an assessment of the many current systems’ capabilities, a roadmap for the specific IM strategies required to support the DOOS science vision can be developed. Instead, we present below a set of guidelines for IM strategy development.

Promote Open Data. To the degree possible within national and funding restrictions, DOOS will promote the open and free exchange of scientific data, as described in the Open Data in a Big Data World Accord (Science International 2015) and endorsed by the International Council for Science. This includes accepting the fundamental responsibility of sharing science data:

Publicly funded scientists have a responsibility to contribute to the public good through the creation and communication of new knowledge, of which associated data are intrinsic parts. They should make such data openly available to others as soon as possible after their production in ways that permit them to be re-used and re-purposed.

An open data policy will seek to generate a ripple effect that accelerates the ocean and Earth observation community's progress toward the application of the benefits of deep- ocean observations across multiple scientific disciplines, and increased use of the data and information as applied to the understanding and addressing of societal issues globally. The benefits of data sharing in furthering scientific progress are well known. As one example, the TAO array, a tropical Pacific Ocean antenna for detecting El Niño and La Niña, was a highly visible pioneer in an open data policy in the arena of physical oceanography. Numerical data and products including many different types of plots were made available in real time via the internet. This open policy generated a very high level of data use in the research community, as well as an increasing reliance on the data for seasonal climate predictions made by weather and climate services -- resulting in very large economic benefits for society.

More recently, the global Argo array of profiling temperature and salinity measuring floats has adopted an open data policy with similar benefits in terms of burgeoning scientific and operational user communities. The global nature of Argo means that it is increasingly useful in initializing operational models and data assimilation products. Argo array data products are used for hindcasting, nowcasting, and forecasting, and more recently are being used experimentally for initializing models for decadal climate prediction.

The importance of open data is particularly important in Deep Ocean Observing science, where lack of data limit scientific progress, and missing data from the historic record cannot be reproduced. DOOS will promote the open sharing of data through mature repositories, such as those meeting ICSU World Data System (WDS) and the Data Seal of Approval (DSA) Core Trustworthy Data Repository Requirements (Edmunds et al. 2016).

Promote Best Practices for Information Management. In addition to a commitment to open data, DOOS will work to identify and promote best practices relating to data management and data sharing for deep ocean observations. These will include general principles, such as the FAIR guiding principles for scientific data management and stewardship for making data Findable, Accessible, Interoperable, and Reusable (Box X (optional) Wilkinson et al 2016), and the enabling practices of citation and provenance, interoperability, non-restrictive reuse, and linkability named in the Science International (2015) Accord. It will also include the evaluation and promotion of domain specific practices, such as quality control procedures for specific EOVs, and particular standards, vocabularies, and services protocols needed to share deep ocean data effectively. The specific practices endorsed will be identified based on scientific priorities.

Leverage existing information management infrastructure. Deep ocean data are held in many well-established repositories around the world, and many deep ocean projects already have a mandate to contribute data to a specified repository, such as the national ocean data center for their country. It is neither feasible nor efficient to create a new global deep ocean information system designed to hold all deep-sea data. Furthermore, segregating deep sea data from other ocean data is not scientifically desirable: deep water formation can only be studied in the context of surface water movements and properties, Particulate Organic Matter fluxes to the seafloor are best understood alongside surface productivity data, the patterns and processes driving deep biodiversity should be related to shallower communities, etc.

There are also many ongoing efforts to better integrate data across repositories, to identify and promote best practices for data curation and sharing, and to develop standards and protocols to improve data quality, accessibility, and usability. Groups like the Research Data Alliance, the Group on Earth Observations, the Open Geospatial Consortium, and the Ocean Data Interoperability Platform are working internationally on these challenges, and have many national equivalents working within individual countries. Domain-specific groups such as the International Oceanographic Data and Information Exchange (IODE) and Quality Assurance of Real Time Ocean Data (QARTOD) are developing and disseminating protocols specific to various types of ocean data.

DOOS will not duplicate, but will seek to evaluate, contribute to, and supplement these ongoing activities to best meet the needs of the DOOS community. To what degree new IM system components or practices must be developed, vs. having DOOS promote and disseminate existing practices and contribute to and use existing resources, will depend on the specific priorities set forth by the DOOS community.

Identify the requirements and priorities of the deep ocean observing community. Despite the plethora of institutional, national, and international data efforts, no existing information system currently meets the needs of the DOOS science community. Broad dialog among DOOS participants will assist in identifying what partnerships are required to create the information needed to support scientific discovery and address societal issues and assist in decision making. A key element will be identification of DOOS stakeholders. Who will use the data, and how? Specific deep ocean research topics will have specific requirements, and different challenges will have different solutions. Another key element will be to survey the current projects producing deep ocean data to ask whether their data, models and software are shared, and if so through what repository; what are the standards that their information products adhere to; and what capabilities and services do the repositories support? Finally a gap analysis evaluating what IM capabilities are currently a high priority for stakeholders but not supported by existing repositories/IM systems can identify priorities for DOOS IM strategy development.

The creation and execution of a successful data management capability will require a sustained effort, characterized by a commitment across the scientific marine communities, and continual coordination among international counterparts. DOOS will take lead in the needed coordination and consensus-building among a wide range of planning, implementation, and user communities.

PART FIVE
Strategic Roadmap:
DOOS Development and Improvement

Introduction

The development of DOOS, as a GOOS Project will occur in stages. Following the 2016 DOOS Workshop and based on the content provided in the DOOS Consultative Draft Report V5-1, and a community–wide survey of deep-ocean observing programs. The workshop initiated DOOS as a 10-year program in which the deep ocean research community will define and develop observations of essential physical, chemical, geological and biological variables. In addition to the articulation of EOVs, DOOS will explore the societal issues and scientific challenges that drive the need for sustained observation of the deep ocean. There will be an overview of the observing elements currently in place, which platforms and technologies are meeting the needs of the system, and where there is a need for improvement or technology development. There will also be an exploration of the impact and benefit of a standardized and open data policy. Lastly, the workshop will explore strategies for achieving integration through the identification of expert panels, implementation teams, and pilot sites that address of the needs of the deep ocean observing system overall.

At the 2016 DOOS Workshop Terms of Reference (ToR) were drafted to define the scope and focus of the Project. The ToR were approved by the SC meeting at its inaugural teleconference in May 2017. The DOOS Project objectives and ToR are provided below:

Objectives:

The purpose of the Deep Ocean Observing Strategy is to improve understanding of the state of the deep ocean 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 Framework for Ocean Observing and Global Climate Observing System 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
1. *Provide a hub for integration opportunities:*
   a) Act as an agent to coordinate existing deep observing activities across disciplines to form a 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.
2. *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
3. *Develop deep observing requirements*
   - Identify the EOVs specific to the deep ocean and add deep-ocean specifications to existing GOOS EOVs
   - Identify gaps (knowledge, geographic, variables, technical, data) and emerging systems relative to the key science and societal questions
4. *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
5. *Foster availability, discoverability, and usability of deep ocean data.*
   - Promote fit –for-purpose data
6. *Create a common community science implementation guidance / plan for deep-ocean observing*
   - *Advocate for deep observations particularly as outlined within the science implementation plan*

Based on the Workshop proceedings the DOOS Steering Committee (SC) was formed. The SC will guide the work of the Project and its Task Teams (TTs).

1. Biology and Ecosystem EOVs
2. Biogeochemistry EOVs
3. Physics EOVs
4. Data and Information Technology
5. Pilot Sites
6. Solid Earth Context

Name	Country	Affiliation
Co-Chairs		
Lisa Levin	USA	Scripps Institution of Oceanography
Patrick Heimbach	USA	University of Texas at Austin
Henry Ruhl	UK	National Oceanography Centre
Members		
Simone Baumann-Pickering	USA	Scripps Institution of Oceanography
Kristina Gjerde	Poland	International Union for Conservation of Nature
Bruce Howe	USA	University of Hawaii at Manoa
Felix Janssen	Germany	Alfred-Wegner Institute
Katsuro Katsumata	Japan	Japan Agency for Marine-Earth Science and Technology
Deb Kelley	USA	University of Washington
Nadine LeBris	France	Universite Pierre et Marie Currie
Craig Smith	USA	University of Hawaii at Manoa
Paul Snelgrove	Canada	Memorial University
Sun Song	China	Institute of Oceanology, Chinese Academy of Sciences
Adam Soule	USA	Woods Hole Oceanographic Institution
Karen Stocks	USA	Scripps Institution of Oceanography
R. Venkatesan	India	National Institute of Ocean Technology Ministry of Earth Science
Bob Weller	USA	Woods Hole Oceanographic Institution

As required the SC and TTs will create working groups or sub-committees to address specialized as well as cross-cutting issues such as international, inter-agency, and other collaborative engagement and endeavors.

By using a highly collaborative, EOV-based approach the DOOS Project will encourage increased partnerships across the research and operational communities. These partnerships will work to align, assess and improve the readiness levels of requirements, technologies and platforms, and data products that are of common interest to multiple GOOS communities; as well as to other communities conducting deep-ocean observing activities and using the output.

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Appendix A: Authors and Contributors

Executive Committee
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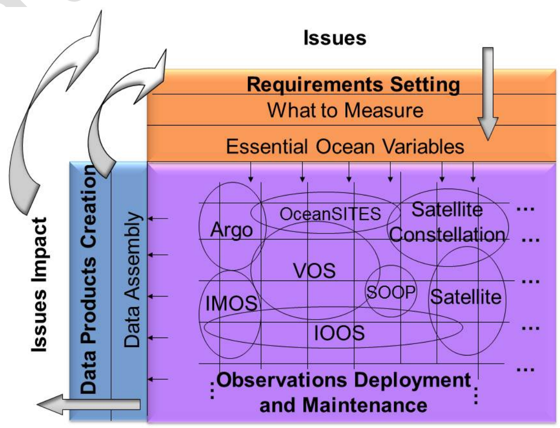
Appendix B: Report Methodology

This report articulates a strategy for measuring the deep ocean in alignment with the guiding principles and practices promoted in the report titled "A Framework for Ocean Observing," (prepared by the Task Team for an Integrated Sustained Ocean Observing System established after the Ocean Observation 2009 Conference in Venice, Italy). The "Framework" recommends that the ocean community adopt a system engineering approach toward the community-wide acceptance of priorities and activities associated with an integrated, sustained global ocean observing system; one that addresses both science questions and societal needs.

The Framework approach as outlined in the report, contends that to maintain a global ocean observing system that is fit for purpose, the outputs of the system must properly address the issues that drove the original need to measure an ocean variable, and establish a feedback loop of assessment that must be maintained by community agreed -upon processes. In order to establish this concerted community effort, the report also recommends that ocean observing activities be organized around community-defined and selected Essential Ocean Variables (EOVs). An EOV is defined as an element of the ocean that the ocean observing community agrees must be measured in order to further scientific understanding of the ocean and Earth systems and their impact on society.

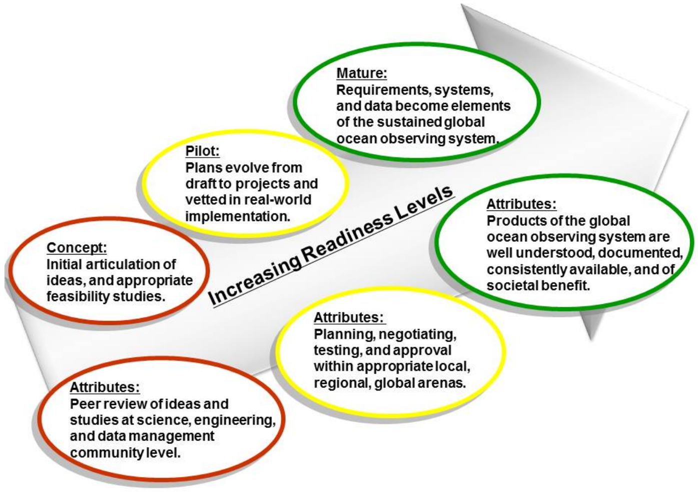
This approach is based on lessons learned from the global climate observing community, which met with great success after organizing its efforts around essential climate variables (ECVs). Essential Climate Variables were introduced by GCOS in 2004, along with the essential data defined for meteorological services by the WMO and have galvanized the climate and weather communities toward the development of a more fully functioning research and observational global ocean observing system for climate.

Beyond an alignment according to EOVs, the Framework report further suggests that what is required to adequately meet scientific and societal needs for a global system, is that the community engage in ongoing dialog as to what are the measurement requirements of an EOV, what are the observational elements (technologies and techniques), and what are the data and information products required to meet user needs. In making these assessments the community is then asked to evaluate the requirements, observational needs, and data and data products according to their readiness levels. Generally this is an assessment as to whether the observing system elements under review are globally relevant such that they justify sustained funding.



From a systems engineering perspective, the inputs (measurement requirements) of the system are best described in terms of the environmental or ecosystem information needed to address a specific scientific problem or societal issue. Societal issues may include a short-timescale need such as hazard warning, or a long-timescale need for information such as knowledge of ecosystem limits required to set sustainable uses of ocean resources.

The processes (observation elements) are the technology used to collect the data needed to address these requirements. The outputs (data and information products) are the syntheses of ocean observations and provide a basis for services and inform scientific problems or decisions about societal issues.



As suggested according to the Framework or systems approach, the criteria for evaluating new components for possible inclusion into the global ocean observing system is in terms of their readiness level. These levels are addressed in three broad categories: concept, pilot and mature. During the concept phase, ideas are articulated and peer-reviewed. During the pilot phase, aspects of the system are tested and made ready for global scale implementation. At maturity, they become a sustained part of the global ocean observing system.

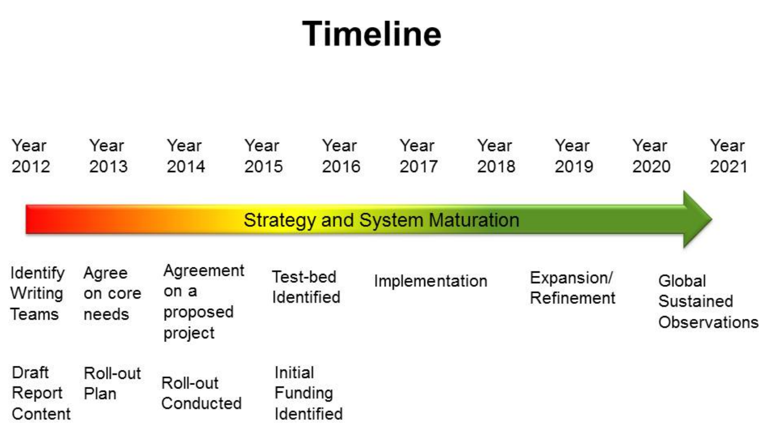
By using a systems approach the authors of this report seek to encourage increased partnerships across the ocean research and operational communities aligned to assess and improve the readiness levels of requirements, observation elements, and data products associated with EOVs proposed for the deep ocean observing system. It is expected that alignment will also enhance collaboration among developed and developing regions, and promote the use of common standards and best practices around the world.

Appendix C: Draft Strategy Timeline

- Writing Group Revises and Updates DOOS Consultative Draft August 2016
- Seek community feedback on Draft Report and form Steering Committee
- Conduct Deep Observation Inventory Sept-Oct. 2016
- DOOS Development workshop to form working groups or teams that frame specific goals

December 2016

- In one year:
  - Established development program
  - Incorporated DOOS in GCOS, CLIVAR, IMBER, INDEEP, DOSI
- In three years:
  - Pilot program underway
- OceanObs 2019
  - Global sustained coverage in sight



Appendix D: ***Current GOOS and Draft DOOS EOVs (December 2016)***

DEEP OCEAN OBSERVING STRATEGY

Global Ocean Observing System and
Deep Ocean Observing Strategy
Essential Ocean Variables
December 2016

<table>
<tr><th>GOOS EOVs</th><th>Proposed DOOS EOVs</th></tr>
<tr><td colspan="2">Biological and Ecological EOVs</td></tr>
<tr><td><u>Proposed</u>
• Phytoplankton (Biomass/Productivity)
• Zooplankton (Diversity)
• Apex Predators (Abundance/Distribution)
• Live Coral Cover
• Seagrass Cover
• Mangrove Cover
• Macroalgal Canopy Cover
• Incidence of Harmful Algal Blooms</td><td>• Primary Productivity
• Element Fluxes
• Remineralization Rates
• Secondary Productivity
• Standing Stock Biomass
• Trophic Interactions
• Physiological Adaptation
• Functional Diversity
• Community Turnover
• Habitat Dimension
• Evolutionary Context
• Community Structure</td></tr>
<tr><td colspan="2">Carbon and Biogeochemistry EOVs</td></tr>
<tr><td>• Dissolved Oxygen
• Inorganic Macronutrients
• Carbonate Systems
• Transient Tracers
• Suspended Particulates
• Nitrous Oxide
• Stable Carbon Isotopes
• Dissolved Organic Carbon</td><td><u>Inorganic</u>
• C of Dissolved Inorganic Carbon (alkalinity, pCO_2, pH)
• Inorganic Nutrients
• Dissolved Oxygen
<u>Organic</u>
• DOM
• POM
• DOC</td></tr>
<tr><td colspan="2">Physics and Climate EOVs</td></tr>
<tr><td><u>Current</u>
• Temperature: Sea Surface, Interior
• Salinity: Sea Surface, Interior
• Currents: Sea Surface, Interior
• Sea Level
• Sea State
• Sea Ice
<u>Proposed</u>
• Ocean Surface Vector Stress
• Sensible and Latent Heat Flux</td><td>• Sea Level
• Temperature
• Salinity
• Transient Tracers: CFCs, SF_6, ^{14}C, ^{39}Ar
• Velocity/Ocean Currents
• Ocean Bottom Pressure
• Geothermal Flux
• Oxygen</td></tr>
</table>

Appendix E: Sustained observatories and observing stations (See Separate Table)

Appendix F: Open Data Policy Statement

Effective management and storage of data are fundamental requirements for successful scientific research endeavors, such that the future of successful oceanographic research will depend on the availability and clarity of long-term data records. Already today, large, multi-investigator, interdisciplinary projects require the timely availability and sharing of data and observations. Implementation of a mature deep ocean data management strategy will result in the timely submission of quality controlled data directly to users, as well as to local, regional, and national data centers for ongoing use.

The FAIR Guiding Principles (from Wilkinson et al. 2016)

To be Findable:

F1. (meta)data are assigned a globally unique and persistent identifier

F2. data are described with rich metadata (defined by R1 below)

F3. metadata clearly and explicitly include the identifier of the data it describes

F4. (meta)data are registered or indexed in a searchable resource

To be Accessible:

A1. (meta)data are retrievable by their identifier using a standardized communications protocol

A1.1 the protocol is open, free, and universally implementable

A1.2 the protocol allows for an authentication and authorization procedure, where necessary

A2. metadata are accessible, even when the data are no longer available

To be Interoperable:

I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.

I2. (meta)data use vocabularies that follow FAIR principles

I3. (meta)data include qualified references to other (meta)data

To be Reusable:

R1. meta(data) are richly described with a plurality of accurate and relevant attributes

R1.1. (meta)data are released with a clear and accessible data usage license

R1.2. (meta)data are associated with detailed provenance

R1.3. (meta)data meet domain-relevant community standards