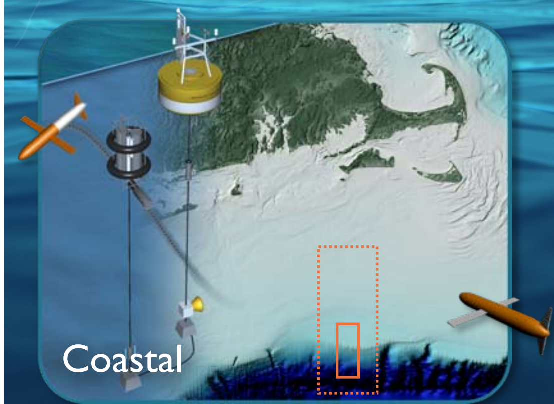
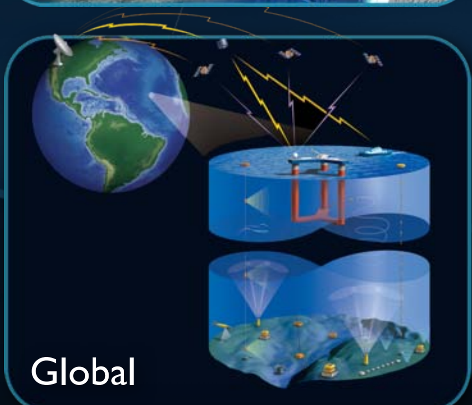
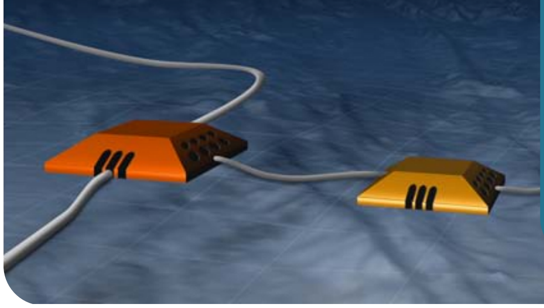
Ocean Observatories Initiative (OOI) Scientific Objectives and Network Design:

A Closer Look







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Executive Summary

Although the ocean is central to the habitability of our planet, it is largely unexplored. Rapid growth in our understanding of the complex exchange among processes throughout ocean basins is severely limited by the paucity of infrastructure able to support sustained and interactive observations of the dynamic ocean environment. Biological, chemical, physical, and geological processes interact in the ocean, at the seafloor, and at the air-sea interface in complex ways. Developing a more fundamental scientific understanding of these relationships requires new and transformational approaches to ocean observation and experimentation.

The Ocean Observatories Initiative (OOI) will enable powerful new scientific approaches by capitalizing on a confluence of "disruptive technologies" that are often related to exponential growth in fields including telecommunications, computer science, and genomics. The OOI will build a networked sensor grid that will collect ocean and seafloor data at high sampling rates over years to decades. Researchers will make simultaneous, interdisciplinary measurements to investigate a spectrum of phenomena including episodic, short-lived events (tectonic, volcanic, biological, severe storms), to more subtle, longer-term changes or emergent phenomena in ocean systems (circulation patterns, climate change, ocean acidity, ecosystem trends). Through a unifying cyberinfrastructure, researchers will control sampling strategies of experiments deployed on one part of the infrastucture in response to remote detection of events by other parts of the infrastructure. Distributed research groups will form virtual collaborations to collectively analyze and respond to ocean events in near-real time. The long-term introduction of ample power and bandwidth to remote parts of the ocean by the OOI will provide the ocean science community with unprecedented access to detailed data on multiple spatial scales, studying the coastal, regional, and global-scale ocean, and using mobile assets (autonomous underwater vehicles, gliders, and vertical profilers) to complement fixed-point observations.

The OOI is based upon a community vision resulting from two decades of workshops, meetings, and reports, which has established science drivers for the proposed infrastructure investment. Examples of science questions are: What processes control volatile exchange at the air-sea interface and within the ocean? Do severe mixing events, such as large storms or eruptions, affect water column processes? Do plate tectonics and seafloor roughness modify fluxes and mixing and influence biological communities in the deep ocean? These and other topics are explored further in the science traceability matrices developed for this document, which are graphical representations showing the logical flow from high-level science questions to the overall design of the proposed OOI infrastructure.

The use of large numbers of interconnected, space- and time-indexed, remote, interactive, fixed, and mobile assets by a global user community, collaborating through the Internet and Internet-enabled software, represents the most fundamental shift in oceanic investigative infrastructure since the arrival of satellites. It will induce major changes in funding strategies, our community structure, the nature of our collaborations, the style of modeling and data assimilation, the approach of educators to environmental sciences, the manner in which the scientific community relates to the public, and the recruitment of young scientists. The discoveries, insights, and the proven new technologies of the OOI effort will continuously transfer to more operationally oriented ocean-sensing systems operated by other agencies and countries. In this manner, OOI will play a key role in keeping the U.S. science effort at the cutting edge of ocean knowledge.

SECTION 1: Introduction

A. Purpose

The Ocean Observatories Initiative (OOI) enabled by the National Science Foundation's Major Research Equipment and Facilities Construction (MREFC) account will create a new research and education platform that will accelerate understanding of the ocean and seafloor and their roles in the planetary environment. It is envisioned that the distributed OOI Network will have a five-year implementation phase and a subsequent 25-year operational lifetime.

The purpose of this document is to articulate high-priority science questions within the broad science themes outlined in the *Ocean Observatories Initiative Science Plan* (1) that will be addressed with the new infrastructure, and demonstrate how answering these science questions requires the infrastructure described in the program's Preliminary Network Design (PND). Section 1 of this document summarizes the project history. Section 2 connects OOI scientific motivation to the design elements using "traceability matrices." Here, the emphasis is on multidisciplinary science questions that require OOI's novel technology to significantly advance understanding. Section 3 is a high-level synopsis of the current network design. Section 4 presents user scenarios that illustrate the spectrum of possible applications of the OOI as a research and education platform, and also addresses potential partnerships, technology development, education, and communications. Section 5 briefly describes the project timeline, high-level budget, implementation entities, and governance model.

This document is intended for a marine science audience and assumes some familiarity with the OOI. Given the length and scope advisable in a program summary, this document does not provide exhaustive motivation for the OOI facility nor attempt to capture the complete history of program planning and development. Instead, it is an overview that concentrates on tracing the connections between science and sensors (traceability matrices), and providing examples of research and education applications. The document was prepared by key personnel involved in the Cooperative Agreement and its major subawards using program plans and reference material, in consultation with key community scientists. It was improved by review from the program's advisory committee. This document, *Ocean Observatories Initiative: Scientific Objectives and Network Design: A Closer Look*, is a revision of an earlier document, *Ocean Observatories Initiative: Scientific Objectives and Network Design* (2), and benefited from the review panel's comments of that effort.

B. Project Background

Biological, chemical, physical, and geological processes interact in the ocean, at the seafloor, and at the air-sea interface in complex ways, strongly influencing our quality of life. This complex ocean system modulates climate, produces major energy and raw-material resources, supports the largest biosphere on Earth, absorbs greenhouse gases, liberates considerable oxygen, significantly influences rainfall and temperature patterns on land, and fuels devastating coastal storms. Ship-based expeditionary research and satellite imagery contribute enormously to our knowledge of the ocean, but the spatial and temporal limitations imposed by these methods mean that many critical ocean phenomena remain unexplored.

The ocean is a challenging environment for collecting data. It is opaque to radio frequencies, it is corrosive, it exerts tremendous pressure at depth, it harbors marine life that fouls sensor surfaces, it can destroy mechanical structures, and most of its volume is not readily accessible and is far from shore-based power sources and signal cables. Progress in developing the capability to collect long-term observations essential to ocean science has been hard won, at times slow, and in many cases remains insufficient. Unlike observational scientists on land, ocean scientists do not have access to sustained high-resolution, multidisciplinary time series, and they cannot routinely run sophisticated analyzers *in situ* or command event-driven sampling responses. At present, most ocean scientists still cannot access their *in situ* data in near-real time because of power and telemetry constraints, requiring them to study events that, at best, occurred months previous. In some locations, such as high latitudes, scientists still lack the capability to deploy long-term moorings that collect data from the sea surface to the seafloor.

The Ocean Observatories Initiative will meet these challenges by building a networked infrastructure for sensors that will collect ocean and seafloor data at high sampling rates over years to decades. These sensors will be linked to shore using the latest communications technologies, enabling scientists to reconfigure them from their laboratories and use the incoming data in near-real time in their models. Scientists and educators from around the country, from large and small institutions, and from fields other than ocean science, will be able to take advantage of OOI's open data policy and emerging cyberinfrastructure capabilities in distributed processing, visualization, and integrative modeling.

Each of the OOI's coastal, regional, and global elements will provide revolutionary ocean-observing capabilities. Copper and fiber cable installed across a tectonic plate will supply continuous power and communications to commandable, multidisciplinary instrument suites. A combination of moorings and mobile samplers (ocean gliders and autonomous underwater vehicles) will collect high-resolution, time-series data at the complicated boundary between coastal and deep-ocean regimes on both the west coast and the east coast of the United States. Moored observatories stationed in the high northern and southern latitude oceans will record information critical to understanding ocean-atmosphere interactions, and ocean dynamics and biogeochemistry. The OOI cyberinfrastructure will make available the distributed observing assets to all users in near-real time, permitting such activities as event-response sampling.

Although the OOI infrastructure will not populate all oceans, nor answer all the pressing ocean science questions, this investment will catalyze ocean science research for decades to come. As this National Science Foundation (NSF) investment is replicated at other locations and adopted by other U.S. agencies and international partners, real-time access to information from all parts of the global ocean will become a reality. The ability to provide sufficient power continuously to complex instrumentation, to retrieve data with minimal delay, and to interact with instruments and platform sampling strategies in near-real time will stimulate the development of more sensors, durable hardware, autonomous vehicles, accurate ocean models, and other observing capabilities. Increased ocean coverage, the growth of technical capability, development of new and more precise predictive models, and increasing public understanding of the ocean will all be tangible measures of the OOI's contribution to transforming ocean science.

C. Project History

Since at least 1988, the ocean sciences community has been developing and refining OOI science, engineering, and outreach concepts. The OOI design developed from two main technical directions: seafloor observatories linked with submarine cables to land that provide power and Internet connectivity; and buoy observatories that provide locally generated power to seafloor and platform instruments and use a satellite link to land and the Internet. A third technical element— integration of mobile assets such as autonomous underwater vehicles (AUVs)—emerged during program planning. The community developed these ideas simultaneously, and NSF nurtured them by supporting numerous related projects and workshops. These activities led to the vision of three observatory scales—coastal, regional, and global—within one distributed, integrated network.

Two National Research Council reports (3, 4) and 14 nationally circulated science and technical reports reflect broad community involvement in this initiative (see Figure 1 for a summary of major milestones in OOI history). In 2000, the National Science Board approved the OOI as an MREFC account project. Two high-visibility documents, the Pew Ocean Commission's 2003 report (5), *America's Living Oceans: Charting a Course for Sea Change*, and the U.S. Commission on Ocean Policy's 2004 report (6), *An Ocean Blueprint for the 21st Century,* also highlight the importance of science-driven ocean observing. Recently, the National Science and Technology Council's Joint Subcommittee on Ocean Science and Technology issued the report *Charting the Course for Ocean Science for the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy,* which identifies the OOI's key role in addressing near-term national priorities (7).

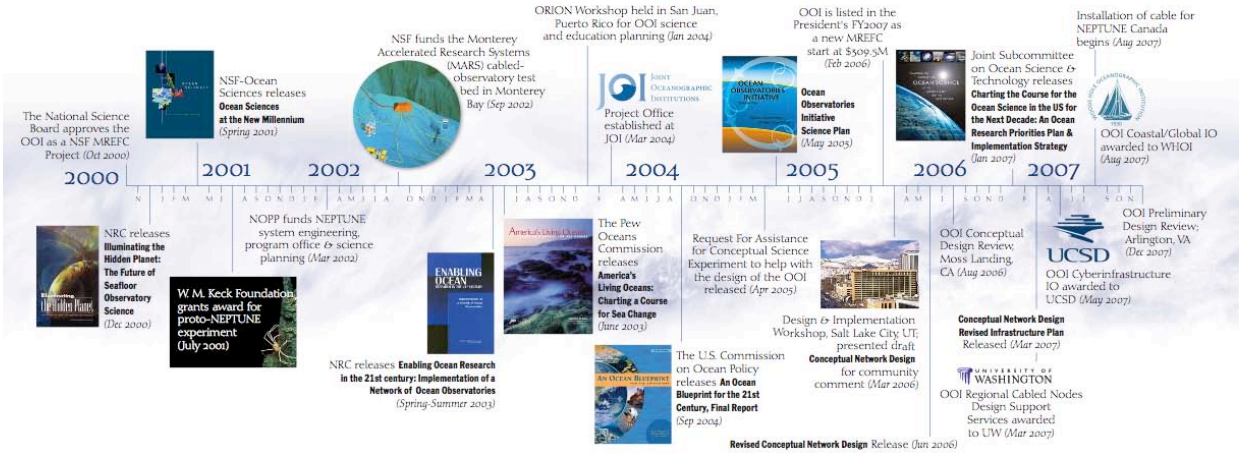


Figure 1. Milestones in the development of the Ocean Observatories Initiative.

In 2004, through a cooperative agreement with the NSF Division of Ocean Sciences, Joint Oceanographic Institutions (JOI) established a project office to coordinate further OOI planning. In 2005, JOI issued a broadly focused request for conceptual proposals (8) that resulted in 48 full experimental design submissions, representing the efforts of 550 investigators and spanning 130 research and education institutions. JOI instituted a large advisory structure of six committees comprising approximately 80 community stakeholders to assist in guiding development of a Conceptual Network Design (CND; 9, 10, 11, 12) informed by these submissions and other program activities. In March 2006, the potential user community reviewed the draft CND at a Design and Implementation Workshop (13). In August 2006, NSF convened a formal Conceptual Design Review to assess OOI scientific goals and merit, the proposed facility's technical feasibility and budget, the project's management plan, including schedules and milestones, and education and outreach plans. In its report (14), the 20-member panel affirmed that the OOI as proposed would transform oceanographic research in the coming decades, and that the CND provided a good starting point for developing the OOI network.

The OOI project office, in consultation with its advisory committees, further refined the CND in light of fiscal guidance from NSF. In March 2007, JOI posted a revised CND for community comment (15), retaining the most transformative ideas that could be addressed within the available budget using parametric cost estimates. The design discussed here has been adjusted from the revised CND in light of more detailed engineering cost estimates, risk assessment, and contingency planning as required by the MREFC account process (16). NSF's current, authorized capital investment for the OOI is $331M, with an anticipated $50M per year in 2013 dollars available as a continuing budget for steady-state operations and maintenance of the network. These budget realities place restrictions on the scope of the facility that will be realized when compared with the more comprehensive, initial concepts.

As historical program documents indicate (17), it has always been intended that OOI infrastructure would be a platform upon which individual investigators could deploy independently funded instruments or experiments for sustained and configurable ocean observing. Prior to 2004, OOI planning focused mainly on infrastructure, rather than scientific instrumentation, in accordance with interpretation of MREFC program policy at that time. The realization that many multidisciplinary scientific goals could be achieved immediately upon completion of OOI infrastructure construction with the addition of a nominal amount of scientific instrumentation (4) led program stakeholders to discuss the concept of "core" sensors, and the guiding principle of striking a balance between initially enabled science and future capability. The OOI design remains focused on making it easy for investigators to plug in their own instruments, opening up research avenues that cannot be imagined today. Engaging the community to use the OOI's capabilities for novel experimentation is a necessary step toward fulfilling the program's potential.

SECTION 2: Science Basis

A. OOI Science Themes

The Ocean Observatories Initiative (OOI) builds upon more traditional approaches to Earth and ocean science by: (1) developing infrastructure that will operate interactively for sustained periods in remote and crucial regions of the ocean, (2) permitting community-wide access to the infrastructure for command and control, and (3) ensuring a community-wide capacity to absorb, manage, and utilize this new data flow to improve understanding and awareness. The OOI infrastructure will permit high-priority scientific research identified by the community in several reports: *Ocean Observatories Initiative Science Plan* (1), *Ocean Sciences at the New Millennium* (18), and *Ocean Research Interactive Observatory Networks (ORION) Workshop Report* (19). The science in these report mirrors many interdisciplinary themes described in *Charting the Course for Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy* (7). Briefly, the OOI Network will provide the necessary infrastructure to advance research in the following areas:

Ocean-Atmosphere Exchange

Quantifying the air-sea exchange of energy and mass, especially during high winds (> 20 ms^{-1}), is critical to providing estimates of energy and gas exchange between the surface and deep ocean, and improving the predictive capability of storm forecasting and climate-change models. Conventional technology has been unable to support observations under high wind conditions.

Climate Variability, Ocean Circulation, and Ecosystems

As both a reservoir and distributor of heat and carbon dioxide, the ocean modifies climate, and is also affected by it. Understanding how climate variability will affect ocean circulation, weather patterns, the ocean's biochemical environment, and marine ecosystems is a compelling driver for multidisciplinary observations.

Turbulent Mixing and Biophysical Interactions

Mixing occurs over a broad range of scales and plays a major role in transferring energy, materials, and organisms throughout the global ocean. Mixing has a profound influence on primary productivity, plankton community structure, biogeochemical processes in the surface and deep ocean, and the transport of material to the deep ocean. Quantifying mixing is essential to improving models of ocean circulation and ecosystem dynamics.

Coastal Ocean Dynamics and Ecosystems

Understanding the spatial and temporal complexity of the coastal ocean is a long-standing challenge. Quantifying the interactions between atmospheric and terrestrial forcing, and coupled physical, chemical, and biological processes, is critical to elucidating the role of coastal margins in the global carbon cycle, and developing strategies for managing coastal resources in a changing climate.

Fluid-Rock Interactions and the Subseafloor Biosphere

The oceanic crust contains the largest aquifer on Earth. Thermal circulation and reactivity of seawater-derived fluids can modify the composition of oceanic plates, can lead to the formation of hydrothermal vents that support unique micro- and macro-biological communities, and can concentrate methane to form massive methane gas and methane hydrate reservoirs. The role that transient events (e.g., earthquakes, volcanic eruptions, and slope failures) play in these fluid-rock interactions and in the dynamics of subseafloor microbial communities remains largely unknown.

Plate-Scale, Ocean Geodynamics

Lithospheric movements and interactions at plate boundaries at or beneath the seafloor are responsible for short-term events like earthquakes, tsunamis, and volcanic eruptions. These tectonically active regions are also host to the densest hydrothermal and biological activity in the ocean basins. The degrees to which active plate boundaries influence the ocean from a physical, chemical, and biological perspective are largely unexplored.

B. Science Traceability

The science motivating the OOI Network is based on input from a broad spectrum of the ocean research community. Numerous reports emphasize the need for simultaneous, interdisciplinary measurements to investigate a range of phenomena, from episodic, short-lived events (tectonic, volcanic, biological, severe storms), to more subtle, longer-term changes in ocean systems (circulation patterns, climate change, ecosystem trends). The introduction of high power and bandwidth will allow the community to complete the transition from mainly ship-based data collection to the management of interactive, adaptive sampling in response to remote recognition of an "event" taking place. Sophisticated cyberinfrastructure tools will enable individual and communities of scientists to tackle their research questions.

Developing the design for the OOI Network is an iterative process of examining the key science questions, the required observations, the technologies needed to support those observations, and in some cases, the environments best suited to making those observations. Analyses of how science questions (from the OOI Science Plan and other NSF science planning reports) lead to the design of proposed OOI infrastructure are discussed below and displayed in the format of a science traceability matrix (i.e., a graphic representation showing the logical flow from high level science questions to the OOI infrastructure elements).

These questions are complex, largely multi-disciplinary in nature, and among the suite of questions identified by the research community as requiring advanced ocean observing technologies and infrastructure.

The examples to follow summarize how the science question is traced to the system capabilities and infrastructure needed to address that question. The traceability matrices show the linkages between science and infrastructure in far greater detail (Appendix A). The OOI infrastructure, instrumentation, and core sensors (i.e., sensors installed as part of the initial investment) will support observational capabilities necessary to make major advances into the broad suite of science questions.

What is the ocean's role in the global carbon cycle? (Appendix A-1)

What are the dominant physical, chemical, and biological processes that control the exchange of carbon and other dissolved and particulate material (e.g., gases, nutrients, organic matter) across the air-sea interface, through the water column, and to the seafloor? What is the spatial (coastal versus open ocean) and temporal variability of the ocean as a source or sink for atmospheric CO_2? What is the seasonal to interannual variability in particulate flux? What is the impact of decreasing pH to ocean chemistry and biology?

One of the most striking geochemical patterns observed in the twentieth century is the rising concentration of atmospheric CO_2. This discovery, made possible through sustained decadal observations, can be compared to changes in the ocean in only a few places because of the lack of comparable observational capabilities, despite the fact that the ocean plays a dominant role in the global carbon cycle and represents the largest reservoir of carbon on Earth. Observations suggest complex processes that make the ocean a carbon sink are being modified as a result of increasing atmospheric CO_2 loading and climate change (20, 21). The exchange of CO_2 between the atmosphere and ocean is mediated by air-sea mixing and ocean ventilation, carbonate equilibrium (the solubility pump), and the conversion of dissolved CO_2 into particulate and dissolved organic carbon by marine phytoplankton and respiratory pathways (the biological pump). The fraction of the biologically fixed carbon that becomes sequestered in marine sediments is mediated by the structure of pelagic ecosystems. These ecosystem processes are predicted to change as increasing ocean CO_2 concentrations decrease ocean pH. Changes to high-latitude food webs, especially in the North Pacific and Southern Ocean, are disproportionately important regions of marine CO_2 biogeochemistry and appear to be particularly sensitive.

The air-sea flux of CO_2 and biological carbon fixation and sequestration rates are highly variable, and understanding interactions between biology and geochemistry in the ocean is a major challenge for the research community. Addressing this question requires data collected at high sampling rates (hours to days) to quantify the importance of episodic events such as storms to air-sea fluxes and carbon-fixation rates. Adaptive sampling capabilities are needed to adjust data-collection strategies during and after an "event." Long-term, decadal time-series data are needed to quantify subtle changes in the location and timing of biologically controlled carbon sinks and air-sea sources.

The Northeast Pacific Ocean and Southern Ocean are subpolar/polar regions considered highly vulnerable to the effects of reduced pH and are regions that are sinks for atmospheric CO_2. Thus, they are prime locations to site sensors that can obtain long time series. At these sites, surface moorings will support core meteorological sensors and in-water sensors with the capability to accommodate additional sensors. Subsurface moorings will be equipped with profilers that can provide high-vertical-resolution data (e.g., physical, chemical, biological core sensors) in the upper ocean to sea surface, and extended vertical profiles to the seafloor. Data collected by gliders will fill in the gaps between the moorings and will provide a mesoscale context required for data interpretation. To complement these data, and to provide a system-wide regional perspective spanning the coastal ocean to the deep sea, time series of the spatial and temporal variability and trends in CO_2 flux, primary productivity and particulate flux, and changes in ocean systems will also be collected over a range of shelf systems.

How important are extremes of surface forcing in the exchange of momentum, heat, water, and gases between the ocean and atmosphere? (Appendix A-2)

What is the effect of extreme (high wind and waves) surface forcing on air-sea fluxes of mass and energy? What is the effect of extreme wind on the structure of the upper mixed-layer? What are the air-sea fluxes of aerosols and particulates?

Improving the knowledge of the mechanisms underlying air-sea exchange is crucial to the interpretation of larger-scale physical and biogeochemical processes. The lack of observations at the air-sea boundary during high wind and sea states is a serious impediment to our understanding of air-sea exchange during extreme atmospheric forcing. Ships are not generally effective sampling platforms in severe weather conditions. Thus, measurements of the exchange of mass (including gases, aerosols, sea spray, and water vapor), momentum, and energy (including heat) across the air-sea interface during high wind conditions (> 20 ms^{-1}) are rare. The availability of these data has been identified as critical to improving the predictive capabilities of storm forecasting and climate-change models, and for estimating energy and material (e.g., carbon, nitrogen) exchange between the upper and deep ocean. Severe storms and other extreme events can greatly affect coastal populations, and so are of particular interest to federal operational partners such as the National Oceanic and Atmospheric Administration (NOAA) and the Department of Homeland Security (DHS).

Continuous measurements above and below the air-sea boundary for periods of years to decades will provide the data needed to understand extreme surface forcing of episodic, seasonal, annual, and decadal processes. Measurements will be taken just above and below the sea surface that in the past have been difficult to obtain with standard moored sensors, especially in regions of high wind. The OOI platforms will have sufficient stability and power to support a suite of rugged meteorological and in-water sensors to enable studies of the dynamics of marine storms, upper ocean circulation, primary productivity, ocean carbon fluxes, and climate. Real-time communications will enable adaptive sampling of subsurface measurements to assess the efficacy of the gas exchange during the storm events, and real-time data will be used to derive parameterizations for coupled air-sea models.

In what ways do severe storms and other episodic mixing processes affect the physical, chemical, and biological water-column processes? (Appendix A-3)

What are the effects of variable strength storms on surface boundary layer structure and nutrient injection into the photic zone? How do storm-induced nutrient injections influence primary productivity, and vertical distribution and size structure of particulate material?

Water column mixing is central to driving ecosystem productivity by replenishing nutrients to the euphotic zone; however, if mixing is too vigorous, overall productivity is suppressed by light limitation. The nonlinear interaction between mixing and light availability, and the corresponding ecosystem response, remains a central question to biological and chemical oceanography. These nonlinear processes impact overall phytoplankton community composition, which in turn affects entire food webs. In the past it has been difficult to measure the impact of mixing on ecosystem dynamics. Traditional approaches have not allowed scientists to maintain a persistent presence in the ocean to quantify the role of high- and low-frequency mixing events. The relative role of episodic and seasonal mixing events on the overall productivity of marine ecosystems remains an open question; their importance relative to large cyclical phenomena (El Niño Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation) remains difficult to evaluate.

The OOI will provide the infrastructure to persistently observe mixing processes in the ocean and assess the corresponding impact on the marine ecosystems. The distributed OOI assets will measure parameters necessary for studying air-sea exchange processes, mixed-layer depth dynamics, material exchange across the base of the mixed layer, internal wave dynamics, the evolution of benthic boundary layers, and changes in the composition and size distribution of the phytoplankton. The measurements will be made on horizontal scales of meters to kilometers and vertical scales of millimeters to meters. Water column data will be collected at high frequency by profiling moorings, including the critical upper 200 m. Data collected by the profiling moorings will be spatially extended by running coordinated transects of AUVs and gliders. Observations of resuspension and benthic boundary layer dynamics will be enabled with sensors mounted at several depths above the seafloor.

The broadly distributed OOI sensor network will measure numerous parameters, from the deep sea to the near-shore coastal ocean, which will enable comparisons of a range of ecosystems. The high-latitude subpolar sites are representative of regions with severe weather, high CO_2 flux, and oligotrophoic and High Nutrient Low Chlorophyll (HNLC) areas. Data from the Pacific Northwest will provide information on a prototypical wind-driven upwelling/downwelling system characterized by a narrow continental shelf, highly variable seafloor topography, buoyant river plumes, and immediate connectivity with the open ocean. These data will be compared to those collected from the contrasting regimes such as the Middle Atlantic Bight, which has a broad continental shelf where mixing is impacted by warm core rings, detached bottom boundary layers at the shelf-slope front, and the frequent passage of severe storms impacting one of the most strongly stratified ocean systems on Earth (often a temperature gradient of over 20 degrees within 2–3 meters in the summer).

How does plate-scale deformation mediate fluid flow, chemical and heat fluxes, and microbial productivity? (Appendix A-4)

What are the temporal and spatial scales over which seismic activity impacts crustal hydrology? How do the temperature, chemistry, and velocity of hydrothermal flow change temporally and spatially in subsurface, black smoker, diffuse, cold seep, and plume environments? How are these systems impacted by tectonic and magmatic events?

The oceanic crust is the largest fractured aquifer on the planet. Thermally driven fluid circulation through the oceanic crust profoundly influences the physical, chemical, and biological evolution of the crust and ocean. Fluid circulation within this aquifer provides heat and nutrients that sustain a vast biosphere at and below the seafloor. Despite some progress in sampling these environments, many of the most important fundamental questions remain, such as what is the depth and extent to which microbial life occurs within the subseafloor, and what is the relationship between submarine plate-tectonic and sedimentary processes and seafloor and subseafloor ecosystems? Transient events such as magmatic eruptions at mid-ocean ridges increase nutrient (e.g., carbon dioxide) output and water venting volume by as much as a factor of one hundred, resulting in extensive microbial blooms and the growth of chemosynthetic communities at the seafloor. Organisms sampled from high-temperature ecosystems at deep-sea hydrothermal vents have challenged our understanding of the physical and biochemical conditions under which life not only exists, but thrives. Biotechnical research of this vast biosphere is leading to the development of pharmaceuticals important in fighting disease and infections, and biocatalysts (enzymes) that are more efficient, thermally stable, and cost-effective than synthetic catalysts important in material processing for industries.

An OOI sensor network on the Juan de Fuca Plate will examine the connection among seafloor spreading, volcanic activity, hydrothermal flow, and the subseafloor biosphere. Because volcanic and tectonic activities are episodic, instruments will be maintained for long time periods so that episodic events can be captured. Some sensors will be located where several-year time-series studies have documented temporal changes in microbial communities following an underwater eruption. Instruments will also supply near-real-time data that will document the connection between crustal strain and subseafloor fluid flow. The Juan de Fuca Plate hosts the highest density of instrumented Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) sites of any place within the ocean crust. Similar to how NEPTUNE (North-East Pacific Time-Series Undersea Networked Experiments) Canada will connect to instruments in the Site 1027 borehole, the OOI will bring near-real time access to data from other ODP/IODP borehole experiments within reach, particularly when instruments provided by individual investigators are considered.

It is becoming increasingly apparent that the effects of magmatic and tectonic events are not limited to the near field. Stress changes induced by fault motions and the passage of seismic waves from distant earthquakes may trigger earthquakes and perhaps even volcanic eruptions. These events have been shown to perturb hydrothermal systems and methane seep environments. To more accurately correlate individual vent or seep activity to plate-scale events, the OOI infrastructure on the Juan de Fuca Plate will acquire data from seismometers, flow gauges, and chemical and biological sensors in arrays. Seafloor observatories are equally important for understanding the progressive changes in venting systems and the biological communities that occur between major events. These observatories can also be used to examine shorter-term perturbations in flow such as those that arise from tides.

What are the forces acting on plates and plate boundaries that give rise to local and regional deformation and what is the relation between the localization of deformation and the physical structure of the coupled asthenosphere-lithosphere system? (Appendix A-5)

What is the style of deformation along plate boundaries? What are the boundary forces on the Juan de Fuca Plate and how do the plate boundaries interact? What are the causes and styles of intraplate deformation? What is the return flow from the ridge to the trench? How much oceanic mantle moves with and is coupled to the surface plate? How and why do stresses vary with time across a plate system?

Tectonic plates are the fundamental building blocks of the lithosphere, and their active boundaries display abundant earthquake and volcanic activity. The Juan de Fuca Plate in the Northeast Pacific Ocean exhibits all major types of oceanic plate boundary—subduction zone, mid-ocean ridge, and transform fault—within a relatively small area. As a consequence, whole-plate seismological and geodynamic observations there enabled by a network of broadband seismometers with associated hydrophones will permit investigation of processes that control the formation, evolution, and destruction of the plate and of the interactions of that plate with the leading edge of a continental margin. Observations of seismicity—particularly, its temporal and spatial distribution, and variations in intensity—will also provide insight into the nature and causes of stress variations with time across the entire plate, the styles and causes of intra-plate earthquakes, the episodic nature of submarine volcanism, and the coupling of forces across plate boundaries. Additionally, such a network will provide a regional context for other, more local experiments with apertures on the order of kilometers.

A plate-scale seismic array will also facilitate studies of the structure and evolution of the lithosphere-asthenosphere system by enabling finer resolution of the seismic velocity structure in three dimensions. In combination with data from land-based studies, a plate-scale seismic array will allow imaging of the deep and shallow structure that accompanies plate formation, evolution, and subduction. Such work will contribute to our understanding of mantle melting, the mechanical coupling of the asthenospheric mantle to the lithosphere, the pattern of return flow from trench to ridge, the nature of mantle flow near contrasting plate boundaries, the rheology of the mantle, and the importance of three-dimensional plate-scale structure for localizing and influencing seismogenic deformation.

How do tectonic, oceanographic, and biological processes modulate the flux of carbon into and out of the submarine gas hydrate "capacitor," and are there dynamic feedbacks between the gas hydrate reservoir and other benthic, oceanic, and atmospheric processes? (Appendix A-6)

What is the role of tectonic, tidal, and other forces in driving the flux of carbon into and out of the gas hydrate stability zone? What is the significance of pressure change on hydrate stability *and methane fluxes due to winter storms and pressure pulses, and bottom currents interacting with topography? What is the fate of hydrate/seep methane in the ocean and atmosphere?*

A significant amount of the methane near Earth's surface is locked into gas hydrates in shallow sediments on continental margins. These gas hydrates may act as a capacitor in the carbon cycle by slowly storing methane that can be suddenly released into the ocean and atmosphere. It is important to understand the degree to which gas hydrates permeate seafloor and subseafloor environments, and the role they play in modulating carbon flux among the solid Earth, hydrosphere, atmosphere, and biosphere. Long-term observations are required to constrain hypotheses about system evolution and response to transient internal and external forcing events.

Hydrate Ridge in the central Cascadia accretionary complex is one of the best-studied gas hydrate deposits. Seafloor venting and formation of gas-rich hydrate deposits near the seafloor have been documented there through ODP drilling and by a series of seafloor studies using submersibles and Remotely Operated Vehicles (ROVs). These studies provide a basis for understanding how gas hydrates are distributed in marine sediments and the processes that lead to heterogeneity in this distribution. In this area, the subseafloor has been imaged with three-dimensional seismic data, which define a focused plumbing system that provides clear targets for observatory instruments. Data from observatory sensors will help to define the temporal evolution of this gas hydrate system, determine material fluxes from the earth into the ocean, and understand biogeochemical coupling associated with gas hydrate formation and destruction.

The stratigraphically controlled plumbing system at Hydrate Ridge contrasts with the gas hydrate system explored on the northern Cascadia margin in scientific ocean drilling programs. Here, fluid flow appears to be controlled by structures that cut across stratigraphic horizons. The central and northern Cascadia margins also provide a strong contrast in lithology, with much greater abundance of coarse-grained sediments in the north, which affects the nature of gas hydrate deposition. Collecting long-time-series data at both Hydrate Ridge and central and northern Cascadia will lead to a comprehensive understanding of gas hydrate processes as a function of lithology, stratigraphy, and structure. The observatory will include fluid samplers, seafloor cameras, *in situ* chemical sensors (e.g., CH_4, H_2S), IODP borehole sensors with increased sampling rates, and repeat high-resolution seafloor bathymetric, imaging, and plume surveys by autonomous vehicles with docking capabilities. As many of the key processes associated with gas hydrate systems occur over short time scales (e.g., gas hydrate release due to small and large earthquakes), real-time data transmission and the capability for adaptive response and sampling adjustment are fundamental "transformational" requirements to enable advancements in this research.

How do cyclical climate signals at the El Niño Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Oscillation time scales structure the water column, and what are the corresponding impacts on ocean chemistry and biology? (Appendix A-7)

What are the effects of climate signals on variability in water column structure, nutrient injection in the photic zone, primary productivity, and vertical distribution and size structure of particulate material? Are secular climate change trends detectable in the oceans?

Atmospheric forcing at seasonal to inter-decadal time scales strongly influences the structure of marine food webs. Understanding when and how marine ecosystems shift between equilibrium states is a widely debated and central issue for both the research and marine resource management communities because many ocean food webs appear to be undergoing major shifts. For example, limited time series in the subtropical North Pacific Ocean show substantial changes in the phytoplankton, zooplankton, and pelagic fish biomass during the mid-1970s and 1980s. Early evidence indicates another shift may have occurred in the late 1990s. The North Atlantic has also exhibited recent shifts in circulation, with corresponding declines in copepod and cod stocks.

Untangling and understanding the causes, processes, and consequences of the different ocean climate cycles is an important problem confronting oceanographers. These cycles span years to decades upon which episodic events (e.g., storms) are superimposed. Thus, scientists require high-frequency (minutes), sustained (decades) time-series data across a range of ecologically relevant spatial scales. High-frequency data are needed to resolve the physical structuring of marine food webs, which can be heavily influenced by short-lived episodic events. The OOI network of distributed assets will measure atmospheric and *in situ* physical, chemical, and biological properties. Vertical resolution of the system will range from less than one meter to tens of meters; horizontal resolution will range from meters to hundreds of kilometers. For many of the ecosystem questions, OOI data will resolve the chemistry and the particulate matter in the upper 200 m of the water column. Given that many of the signatures of these large-scale processes are resolved at local and regional scales, the network will include coastal and global sites. Network nodes in the North Pacific will obtain data on the El Niño Southern Oscillation and Pacific Decadal Oscillation cycles, while nodes in the subpolar and subtropical Atlantic will resolve the impact of the North Atlantic Oscillation. A node in the subpolar Southern Ocean will fill critical gaps in current data sets.

How does topography-driven mixing maintain the observed abyssal stratification? (Appendix A-8)

What processes are responsible for enhanced near-boundary mixing? How is heat transported into the ocean interior? What is the role mean seasonal versus episodic processes? What is the importance of the abyssal stratification and how is it maintained?

To date, the available data implies that there is insufficient turbulence in the deep interior oceans, away from the boundaries, to produce enough vertical mixing to account for the vertical profile of temperature. In short, the deep ocean is warmer than it should be given observed levels of *in situ* turbulence that can mix surface heat downward. Surface heat in the tropics and subtropics has to be mixed downward to balance the upwelling of the cold bottom waters formed at high latitudes that disperse into all ocean basins. Without some mechanism of downward mixing of heat, in about 3000 years the entire ocean beneath the thermocline would fill up with the very cold water created at high latitudes. Formation of such a deep, thick isothermal layer would have serious physical, biological, and climatic implications, including the cessation of the very convection of cold water that created it, thus halting the pull of warmer subtropical water toward the poles, especially in the far North Atlantic. This Meridional Overturning Circulation (MOC), considered an important contributor to the relatively warm climate of Europe, would cease to exist. This, at least, is one highly regarded hypothesis of the importance of the abyssal stratification. Understanding how the abyssal stratification is maintained is a critical issue for understanding potential variations in the MOC and resultant climatic impacts.

Observations in the past 15 years have uncovered enhanced levels of turbulence near the water-earth boundary in regions of rough and acute topography. The proposition, now well established, is that the required vertical mixing to maintain the abyssal stratification occurs near regions of strong topography, with the mixed products being distributed horizontally by mesoscale eddies and "mean" currents. Many physical mechanisms have been identified as possible contributors to the topography-catalyzed mixing. Through rapid sampling of physical variables over long periods of time, scientists will be able to sort out the nature of these mechanisms, their relative importance, their temporal and spatial variability, their dependence on changes in environmental factors (e.g., mesoscale current strength, internal wave energy levels), and how they can be parameterized in models of the ocean's general circulation and climate. The OOI Network will provide continuous and plentiful power to support numerous sensors, high-bandwidth data communications, and the needed observational infrastructure to tackle these important questions.

What are the dynamics of hypoxia on continental shelves? (Appendix A-9)

What are the relative contributions of low-oxygen, nutrient-rich source water, phytoplankton production from local upwelling events and along-shore advection, and local respiration in driving shelf water hypoxia? What are the impacts of shelf hypoxic conditions on living marine resources? How are wind-driven upwelling, circulation, and biological responses in the coastal zone affected by the El Niño Southern Oscillation, water mass intrusions, and inter-decadal variability?

Unlike hypoxic events fueled by anthropogenic nutrients and limited circulation of semi-enclosed estuaries or embayments, hypoxia on the continental shelf is driven by atmospheric forcing, upwelling/downwelling, and variability in ocean circulation. Low dissolved oxygen concentrations have been documented in the coastal waters off Oregon during late spring to summer of 2002 to 2007. Some events were accompanied by mass die-offs of commercially important shellfish and finfish. Large regional-scale oxygen depletions have also been documented on the Middle Atlantic Bight. Upwelling brings nutrient-rich, oxygen-poor deep waters onto the shelf, fueling phytoplankton blooms, which, in turn, reduce oxygen levels in the near-seafloor water column through decomposition. In contrast, the 2002 event was triggered by an invasion of low-oxygen, subarctic water from the Gulf of Alaska, depressing dissolved oxygen levels in offshore waters from Vancouver Island to southern Oregon. The formation and duration of hypoxic areas are subject to climate variability and variations in upwelling/downwelling and oceanic flow on seasonal, interannual, El Niño Southern Oscillation, and inter-decadal scales. Understanding hypoxic events and impacts to marine ecosystems requires the ability to observe physical, chemical, and biological conditions across the continental shelf to slope waters, for periods spanning years (seasonal to interannual change) to decades (El Niño Southern Oscillation and Pacific Decadal Oscillation shifts). This is an especially pressing problem as the impact of the low-oxygen water can trigger mass mortalities in high tropic levels.

OOI's distributed network of fixed and mobile platforms will permit studies of the frequency, intensity, and mechanisms driving the invasion of low dissolved oxygen water on continental shelves. Large, three-dimensional data volumes collected by gliders will provide detailed information for making maps of the low dissolved oxygen waters; gliders will also adaptively map the spatial extent and morphology of the low dissolved oxygen intrusion. For studies of coastal ocean processes, from event-scale changes, to interannual variability, to interdecadal trends, data will be collected by permanent and movable instrumented arrays that have sufficient power and bandwidth to support multidisciplinary sensors. These nodes will also collect time series of the gradients in physical and biogeochemical properties across the continental shelf and slope. By combining these data with simultaneous observations of the meteorological forcing and oceanic flows measured at high vertical resolution, scientists will be able to study the corresponding chemical and biological response to the low dissolved oxygen water.

How do shelf/slope exchange processes structure the physics, chemistry, and biology of continental shelves? (Appendix A-10)

What processes lead to heat, salt, nutrient, and carbon fluxes across shelf-break fronts? What is the relationship between the variability in shelf-break frontal jets and along-front structure in coastal organic matter? What aspects of interannual variability (in stratification, offshore circulation patterns, jet velocities, and wind forcing) are most important for modulating shelf/slope exchange of dissolved and particulate materials?

There are numerous shelf/slope exchange processes that transfer significant amounts of heat, salt, and organic matter between continental shelves and the deep sea. These mechanisms are highly variable in space and time; many operate over kilometer scales in the horizontal dimension, but may only span meters in the vertical. Exchange may last only a few days; extreme events such as storms appear to play a large role in sustaining exchange and dissipating heat, salt, and organic matter. Traditional shipboard sampling cannot provide sufficient spatial and temporal resolution to constrain, much less quantify, these shelf/slope processes and as a result it is not possible to derive robust budgets for carbon, heat, salt, and other properties on continental shelves. These deficiencies contribute significantly to our inability to quantify the flux of carbon between continental shelves and the deep sea. These shelf/slope exchanges are also critical in structuring continental shelf food webs because megafauna are often known to congregate at locations of intense exchange.

High-frequency spatial and temporal data collected by the OOI Network on the U.S. east and west coasts will enable scientists to quantify these exchange mechanisms and identify their impact on shelf/slope biogeochemistry. Because exchange can vary in location along the shelf/slope due to the passage of offshore features (e.g., warm/cold core rings), collecting real-time, *in situ* data will permit adjustment of AUV volumetric sampling patterns. Profilers will collect high-frequency data to characterize the water column, from the seafloor to the sea surface, to capture the properties of water masses as they pass through the array. Meteorological measurements will be taken so that the impact of wind forcing on exchange can be studied. Given that the many of the shelf/slope waters are optically complex, the sampling strategy will include optical characterization of dissolved and particulate material to describe the distribution of constituents (e.g., sediment, phytoplankton, detritus). To enable future studies of other shelves and processes, the array itself will redeployable at the completion of the initial study.

C. Implications for Network Design

Although there is great variety in the science that the OOI will address, there are many common requirements for observations, sensors, and sampling. Common to most the key science questions is the fundamental need for vertical profiles of basic water column properties (along with profiles for specific measurements of interest) and the capability to control the temporal and vertical resolution of sampling. An associated requirement is high-resolution sampling in the upper water column (i.e., where air-sea exchange and forcing, primary biological processes, and the link between atmosphere and deep ocean occur). Questions addressing plate-scale geodynamics, fluid-rock interactions, and subseafloor conditions also need measurements of near-seafloor water column properties. These common sampling requirements point to profiler technologies capable of sampling from sea surface to seafloor throughout the OOI Network. In addition to profilers, multidisciplinary sensor suites will require the high power, bandwidth, two-way communication, and "permanence" provided by cabled moorings.

Questions concerning interannual variability of ocean circulation and biological processes as influenced by changing climate indices require the sustained, long-term observations of an enduring array of moorings and benthic nodes. A suite of long-term air-sea, water column, and seafloor observation capabilities is needed to enable research into the relationships between climate forcing and marine ecosystems.

Several key questions feature the role of episodic events, requiring both continuous and adaptive sampling to capture the system conditions leading up to, during, and after an event. Events can include (but are not limited to) severe storms, phytoplankton blooms, earthquakes, tsunamis, and submarine volcanic eruptions. The OOI infrastructure and sensors must support observations in extreme conditions and must be sufficiently stable to withstand shocks and heavy weather, leading to the need for highly stable and capable platforms.

Processes of plate-scale geodynamics and the associated questions about fluid-rock interactions and the subseafloor biosphere require locations in which these phenomena can be observed. Infrastructure capable of supporting benthic, subseafloor, and ocean instrumentation will enable studies of complex, coupled geophysical, geochemical, and biological questions. The power, communications, and in some cases, remote sensor locations can be accommodated by a plate-scale cabled network.

Capable global platforms with power sufficient to support measurements of basic meteorological parameters, dissolved gases, and the basic physical and ecological parameters governing carbon fixation and sequestration at high latitudes are required to address questions of spatial variability of the ocean as a source or sink for atmospheric carbon dioxide. High-latitude areas identified as large CO_2 sinks or that have high CO_2 inventories are also areas that routinely experience extreme wind and sea states, deep mixing, and so are well suited to addressing questions concerning the role of severe storms in ocean processes. The need to understand the role of continental shelves in air-sea CO_2 exchange leads to the requirement for CO_2, surface meteorology, and upper-ocean physical and ecological measurements.

Detailed study of the physical and biological processes associated with the continental shelf and shelfbreak fronts requires arrays of instrumented and appropriately spaced moorings. This design element would provide higher-resolution volume descriptions of properties and mesoscale physical processes along and across the shelf.

The heterogeneities of most ocean phenomena point to the need for the enhanced sampling capabilities provided by mobile sensor platforms, specifically AUVs and gliders. AUVs and gliders enable adaptive and spatially expanded sampling to augment measurements made on fixed moored platforms, providing contextual information to augment measurements made from fixed assets.

SECTION 3: Network Design

This section briefly describes the high-level design of the OOI infrastructure. The locations of planned assets are shown in Figure 2. As discussed in Section 1C (Project History), the design is an evolution from the Conceptual Network Design, adjusted to fit within the expected ceiling for capital investment and operations and maintenance. As of this writing, engineering cost estimates and feasibility studies are still underway in preparation for Preliminary Design Review; however, the assets at the level described here are not anticipated to change substantially. The infrastructure descriptions below are generally in line with the budget estimates presented in Section 5.

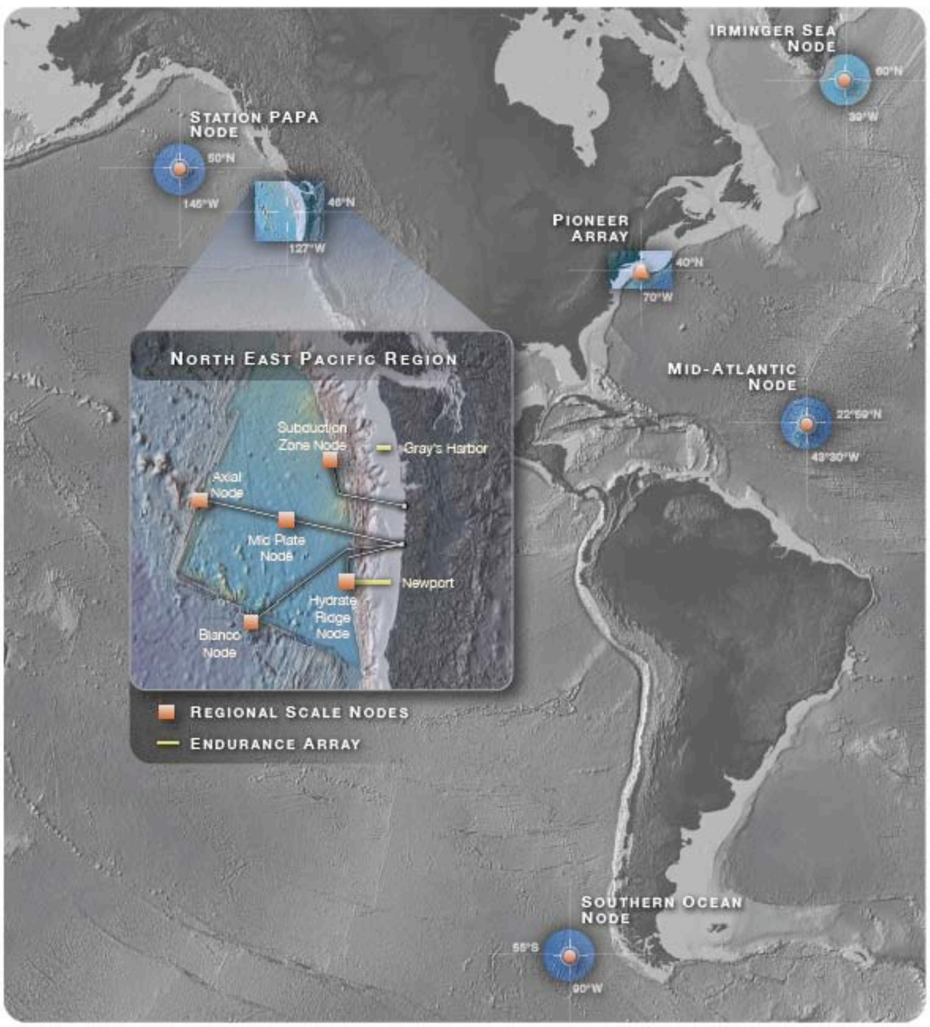


Figure 2. Geographic locations of the OOI network infrastructure: the four Global-Scale Nodes (Southern Ocean, Irminger Sea, mid-Atlantic, and Station Papa); the Regional-Scale Nodes in the North East Pacific; and the Coastal-Scale Nodes including the Endurance Array off Oregon and Washington, and the Pioneer Array in the Middle Atlantic Bight.

A. Guiding Principles

The National Research Council report "*Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories*" included design goals that reflect the ocean science community's vision of OOI capabilities. Many of these design criteria are echoed in the traceability matrices in Appendix A, and in the previous section, which described the implications for network design. As also described in numerous reports, the design goals established in the NRC report remain those required to address broad community science goals: (1) continuous observations at time scales of seconds to decades; (2) spatial measurements from millimeter to kilometers; (3) the ability to collect data during storms and other severe conditions; (4) two-way data transmission and remote instrument control; (5) power delivery to sensors between the sea surface and the seafloor; (6) standard sensor interfaces, (7) AUV docks for data download and battery recharge; (8) access to facilities to deploy, maintain, and calibrate sensors; (9) an effective data management system that provides open access to all; and (10) an engaging and effective education and outreach program that increases ocean literacy.

Taking into account these ambitious design goals and the fiscal realities of the current capital investment, the OOI effort has focused on providing the infrastructure to fulfill as many broad user desires as possible. The program's advisory committee has recently articulated guiding principles for decision-making as the design is refined based on more accurate cost estimates. These include: the importance of supplying power and communications capacity substantially exceeding traditional ocean observing platforms; an emphasis on developing fewer, but more highly capable systems, rather than numerous systems with traditional capability; using a mixed portfolio of fixed and mobile assets to appropriately address science goals; the importance of maintaining the multiscale nature of the overall facility, and integrating across the coastal, regional, and global scales; the recognition that the OOI is a research platform that will enable future experiments and capabilities beyond those included in the initial configuration; and enabling exciting science with the initial core suite of sensors.

B. Interactive Cyberinfrastructure (CI)

The OOI will be a broadly distributed multiscale network of observing assets bound together by an interactive cyberinfrastructure (CI) backbone that will link the infrastructure elements, sensors, and models into a coherent system of systems. The CI will allow access to other (i.e., non-OOI) data streams to provide users with a coherent four-dimensional view of the ocean. Using the OOI CI, scientists will be able to, for example, combine OOI water column data with NOAA and NASA satellite ocean-surface imagery and NOAA Integrated Ocean Observing System (IOOS) subsurface data. These interactive and data-aggregation capabilities will complement parallel international efforts by Canada, Japan, and Europe and have the potential to change fundamentally how ocean science is conducted.

The OOI CI will provide a range of capabilities. In principle, anyone—scientist, engineer, or educator—will have access to two-way interactivity, command and control, and resources (a common term for entities such as instruments, near-real-time data [latencies of seconds for some platforms], historic data archives, and so on). An advanced CI capability will allow data delivery, analysis, and synthesis from across the OOI on a localized semantic frame of reference. The CI will permit mediation among different protocols, data streams, and derived products to test scientific understanding. In accordance with the OOI data policy, calibrated and quality-controlled data must be made publicly available with minimal delay. This will require sophisticated system security, and protocols to control and prioritize access to sensors and data in a shared environment and in accordance with agreed-upon policies in the program's operational framework. Near-real-time, reliable data delivery and interactivity will be important features, enabling shorebased scientists to adaptively adjust sampling strategies.

A traditional data-centric CI, in which a central data management system ingests data and serves them to users on a query basis, is not sufficient to support the ocean science community's OOI requirements. Therefore, throughout the observatory network, strategically placed computation and storage infrastructure will be provided at Cyberinfrastructure Points of Presence (CyberPoPs). These CyberPoPs include integrated, real-time data processing and archive sites located at a few central facilities and at marine observatory shore stations or control centers. CyberPoP capabilities include a secure, highly available, scalable computation design that can be deployed in environments ranging from moorings that may be extremely resource-constrained to the TeraGrid. *In situ* computation and storage resources will be located within science instrument interface modules at the distal ends of the sensor network and selectively within the marine networks. The CI will allow new or updated software to be installed remotely on already deployed instruments to enhance their capabilities or to adapt to changing requirements. The external functions of a sensor (e.g., gain, on/off, power supply level) will be accessible through the cyberinfrastructure. The CI marine CyberPoPs may complement or replace some existing instrument storage and computational resources, depending upon available power and system requirements.

The CI will enable groups of investigators with common interests to construct virtual observatories that combine different groups of physical assets together in an environment that allows others to simultaneously share the same assets. This decentralized, Grid implementation means that the CI is broadly distributed around the globe, and extends the concept of an observatory from one to many without increasing the physical footprint of its wet assets. For example, investigators interested in specific problems would "subscribe" to near-real time data from sensors that specifically address their research topics. To complement the observational data stream, large computational models and simulations can be run on the national grid infrastructure (i.e., the TeraGrid and the Open Science Grid). Near-real-time data from the data streams will be assimilated into global or regional ocean/atmosphere models to "interpolate" the data and predict the ocean state in the future. The knowledge created by the process can, in turn, be used to modify the network itself (e.g., change the sampling plan for an AUV) to enhance the model's fidelity. Thus, the CI blends the conceptual boundaries of the coastal-, regional-, and global-scale observing assets, considering rather the OOI Network as an illuminated grid of sensors, each with a unique Internet Protocol (IP) address.

The CI will be developed in a series of annual releases in order to maintain compatibility with the developing infrastructure over the five-year build of the facility during which community feedback will be critical. The annual CI releases represent the broad demarcation of the major planning and delivery milestones. The CI development process requires that the "development" code base be operational and available for testing on a continuous basis. The plan is to migrate minor releases to the network every three months.

C. Global-Scale Nodes (GSN)

Sustained atmospheric, physical, biogeochemical, ecological, and seafloor observations at high latitudes are required to understand critical influences on the global ocean-atmosphere system. Currently, no capability exists to collect these coincident, multidisciplinary time-series data. The OOI's design process has identified three strategic high-latitude sites and one mid-latitude site for initial global-scale nodes: the Southern Ocean off Chile (55°S, 90°W), the Irminger Sea (60°N, 39°W) in the subpolar North Atlantic, a mid-Atlantic site (23°N, 43.5°W), and Ocean Station Papa (50° N, 145°W) in the Gulf of Alaska (Figure 2). OOI infrastructure will provide the power, bandwidth, and platform space to support more capable sensor packages, bring back as much data in near real time as possible from these under sampled regions, and permit two-way communications to control and change sampling strategies in response to contextual information. OOI's GSN will serve as a foundation and proof of concept of new technology, encourage the development of sophisticated, multidisciplinary sensor suites, and become the basis for future expansions and national and international partnerships that will establish truly global ocean coverage.

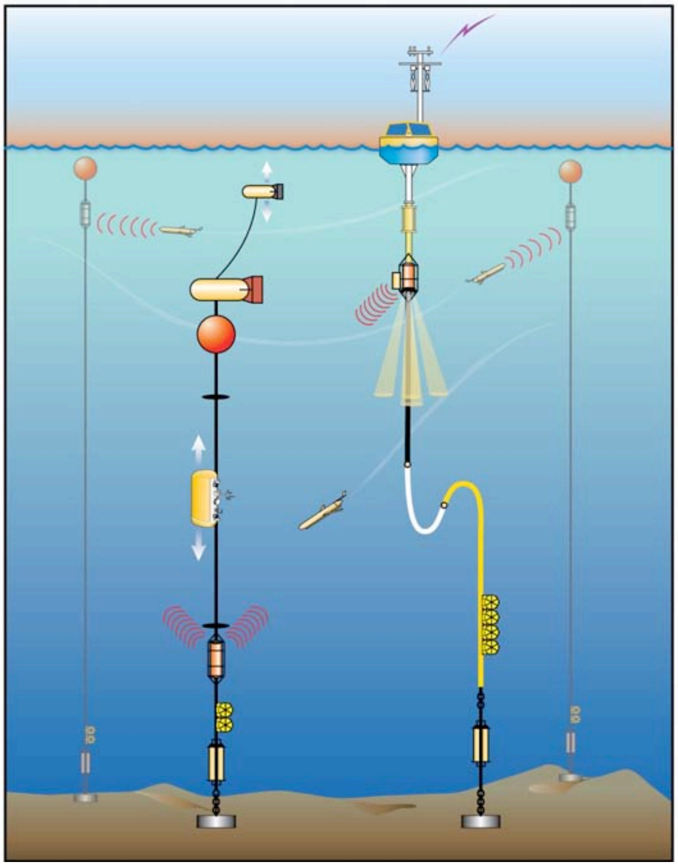


Figure 3. Platforms to be deployed at the high-latitude sites. A surface mooring provides the platform for meteorology and air-sea flux sampling, power generation, and satellite communications. A downward-looking ADCP and other sensors will sample the upper ocean. A subsurface mooring will have an upper profiler capable of penetrating the surface, and lower profilers will sample through the water column to close to the seafloor. Two flanking subsurface moorings and gliders will sample the mesoscale ocean and variability within mooring array. A cable and seafloor junction box can be added.

The planned GSN infrastructure will provide comprehensive surface-to-seafloor observing capability at fixed locations; additional moorings and gliders will provide information on the site's mesoscale context. Paired surface and subsurface moorings will resolve surface forcing, and water column, benthic, and seafloor processes in time and in the vertical, the latter dimension with two profilers spanning the water column. Flanking moorings and gliders will collect data on spatial gradients and advective influences.

The global platform design will initially use two platforms: a discus buoy moored with an inverse catenary mooring employing acoustic telemetry to subsurface instrumentation, and the tri-moored Extended Draft Platform (EDP) that will provide substantial power and bandwidth to the seafloor. The discus buoy, approximately 8–9 m in length and 2.8 m in diameter, will be used at the three high-latitude sites (Figure 3). This buoy will be designed to self-right and carry electronics and storage batteries. A combination of solar (deck-mounted) and wind (tower-mounted) power-generation systems will provide 40–50 W continuous power delivery capability, with a higher peak availability. A mast will provide mounting for air-sea interaction sensors. This design can be launched, maintained, and recovered by the largest University-National Oceanographic Laboratory System (UNOLS) vessels.

The EDP, designed using industry and NSF support and built by industry for the OOI as an approximately $8M contribution, is planned for deployment early in the program so it can generate early science results and provide a testbed site for power generation, communications, and sensor technologies. The EDP (Figure 4) comprises three vertical columns between a deck structure and a submerged pontoon. The EDP will provide a stable platform more than 10 m above the sea surface, with large deck space, diesel power generation of ~10 kW, with an electro-optical (EO) cable to deliver at least 500 W and two-way communications to a seafloor junction box for benthic and borehole sensors and experiments, and C-band, or possibly Ku-band, VSAT communication of at least 500 Mb/day. These capabilities will also allow atmospheric sampling, including remote sensing (LIDAR, Radar), automated radiosonde launching, aerosol sampling, and measurement of the surface radiation budget. An offshore supply vessel assisted by a small offshore tug will install the EDP while a UNOLS vessel with an ROV will install the EO cable and seafloor instrumentation associated with the EDP.

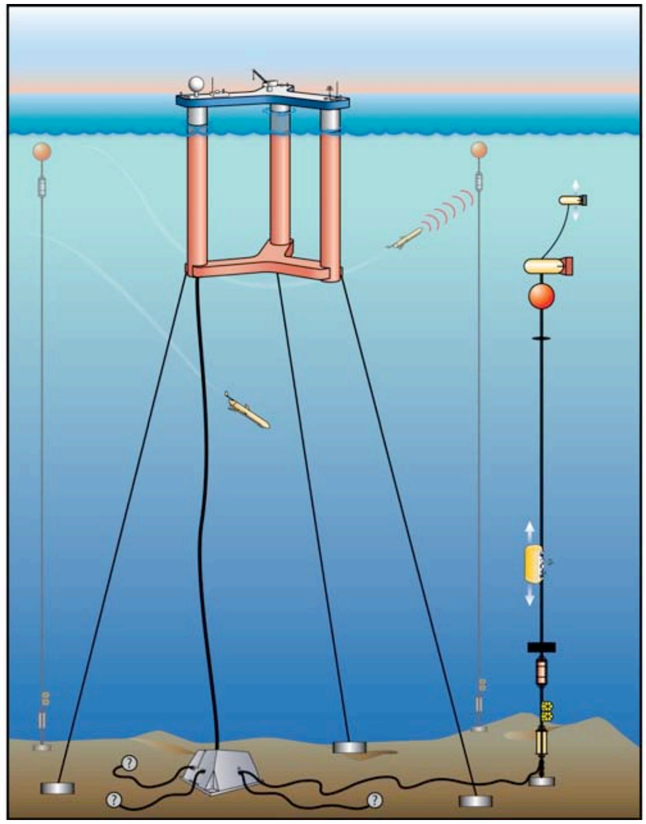


Figure 4. Schematic of the mid-Atlantic global site with the Extended Draft Platform (EDP) installed. As at other global sites, a nearby profiler-equipped subsurface mooring, two flanking subsurface moorings, and gliders will be deployed. An EOM cable to the seafloor from the EDP will provide power to the seafloor and a capable data link back to the surface, supporting seafloor and borehole instrumentation.

Development of a more capable high-latitude buoy, considering both discus and spar designs, with greater power generation (500–1000 W) and a surface mooring with EO or electro-optical-mechanical (EOM) cable to the seafloor is under consideration as an enhancement to the baseline high-latitude design described above. If this proves practical, it will also be used to enhance the OOI’s coastal-scale assets. If the enhanced buoy proves affordable and feasible, it would be first deployed under test near the mid-Atlantic site (EDP) and then staged to the Southern Ocean node. The EDP was designed for the mid-Atlantic site, but its behavior is being modeled at Station Papa and the cost-benefit trade-offs of the EDP and spar buoys vis-à-vis a discus buoy installation is being considered.

Each site will have a subsurface profiler mooring close to the surface mooring; that mooring will have two profilers. An upper profiler will operate from ~150 m to the surface, providing a platform for high-vertical-resolution sampling up to and including at the sea surface. A lower profiler will sample down to the seafloor. Communication within the subsurface mooring and the upper part of the surface mooring will be inductive, while acoustic modems will be used for communication between the subsurface mooring and the surface buoy and to sensors deeper in the water column or on the seafloor. The upper profiler will penetrate the surface, allowing satellite data telemetry. In the future, commitment of remotely operated vehicle (ROV) capability to the global sites would allow cabling to run from the bottom of the surface mooring to a seafloor junction box. This link would provide power generated at the surface buoy to the subsurface mooring and a path for data from the subsurface mooring to the satellite relay hardware on the surface mooring. Surface sensors will support the sought-after accuracy in the air-sea fluxes in high winds and waves. Moored sensors will sample physical, chemical, and biological variability.

Two additional, less-sophisticated subsurface moorings will be deployed to form a triangular array with the central site (~100 km on a side). These taut moorings have their uppermost flotation in the upper ocean and instruments at discrete depths along the mooring line. These ancillary moorings would provide data intermittently, using the gliders for data collection or regular data capsule releases from the moorings. Sampling within and around the triangular array will be done using several gliders. These gliders will carry multidisciplinary sensor suites and sample for a year and can be commanded to alter their sampling patterns.

C. Regional-Scale Nodes (RSN)

The cabled Regional-Scale Nodes (RSN) will provide the ocean sciences community with virtually unlimited bandwidth and considerable electrical power that will enable collection of decadal-scale time-series measurements encompassing an entire tectonic plate, a major coastal upwelling system, a highly variable divergence zone between two North Pacific gyres, one of the most productive fishing areas in the world's oceans, boundary currents on the east and west coasts, and hundreds of kilometers of volcanically and seismically active plate boundaries that focus fluid convection through the crust.

The RSN will be installed in the North East Pacific Ocean on the southern two-thirds of the Juan de Fuca Plate, with the complementary NEPTUNE Canada system covering the northern third (22) (Figure 5). The backbone infrastructure of the RSN will initially comprise ~1400 km of EO cable, providing high power (10 kW) and high data rates (10 Gigabit Ethernet) and a time base accurate to within 10 microseconds to five primary nodes chosen for their proximity to diverse tectonic features and water column settings as described below. As a consequence, the potential instrumented volume will extend from the seafloor to the air-sea interface over a mesoscale area the size of a tectonic plate, measuring several hundred kilometers on a side. To reach areas of key scientific interest, the cabled systems will include multiple shore stations linked to an Internet Point of Presence by telecommunications backhaul cables.

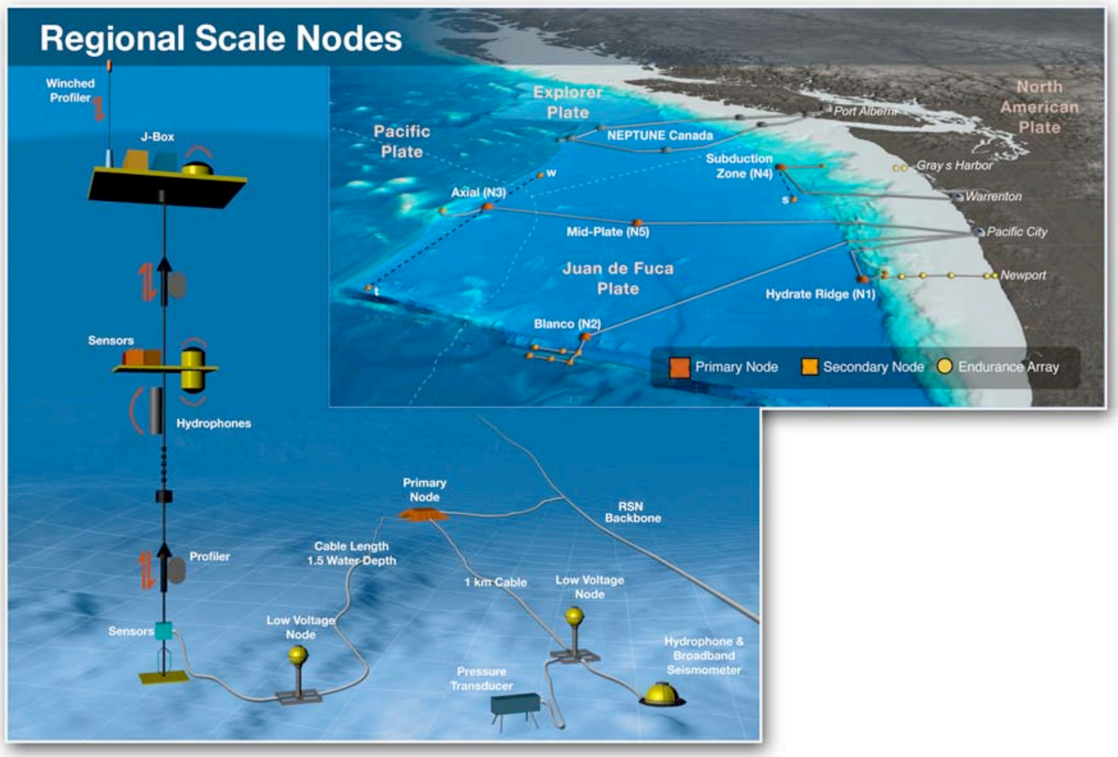


Figure 5. (Right) STAR configuration and location of two shore stations (Warrenton, Pacific City) for the Regional-Scale Node. Future extensions to nodes t, w, and s are not considered in this document, but are shown for completeness. The international territorial boundaries are shown as white dashed lines. Also shown is the connection of RSN N1 to the Coastal Oregon Endurance Array off of Newport, OR. (Left) Illustration of a full water column mooring with profiling and winch capabilities.

The five primary nodes can support multiport expansion nodes, intended to pass on the original power and communications capacity to future infrastructure or experiments, and multiport science nodes, which step down the voltage and communications to variable lower levels (e.g., 400 V and 1 Gigabit Ethernet) more easily converted into instrument-specific input specifications. Benthic junction boxes will further provide various common input/output levels for oceanographic sensors. These proximal, linked nodes and junction boxes clustered geographically within 100 km of the primary nodes will support multiple user experiments or campaigns during the multi-decadal life of the OOI. More detailed information about the planned secondary and tertiary infrastructure is provided in technical design studies (23, 24).

The radial topology of the backbone cable supplying power and two-way real-time communications to the primary nodes offers a significant advantage over earlier ring designs (25) by allowing the use of existing telecommunication technologies, which will provide a lower-risk solution to reach the same node geometry. In addition, the DC power scheme is simpler and more flexible, yet it retains considerable expandability. The use of two shore stations at Warrenton and Pacific City results in significantly fewer crossings of existing submarine cable systems, which reduce insurance and liability risks.

In addition to key experimental infrastructure and sensors associated with the seafloor experiments, water column moorings at the primary nodes will enable interdisciplinary observations—unconstrained by power considerations—of open-ocean processes in a region strongly forced by air-sea interaction, shelf-slope interactions with the deep sea, and coupled atmospheric/oceanic phenomena that produce variations in North Pacific circulation. Although all primary nodes can support water column moorings, initial plans and budgeting call for a phased development and deployment to leverage engineering progress for profiling mooring technology from the coastal and global sites, and a reduced project risk associated with this new development. Based on current engineering cost estimates, two moorings can be accommodated in the budget shown in Section 5, and are planned at the nearest shore site, N1 Hydrate Ridge, which will extend the Endurance Array profiling line, and the deepest water site at Axial Seamount. The program's advisory committee endorses water-column moorings at all sites, and has priority ranked the remaining sites as Subduction Zone (N4, to sample water from the northern current), Blanco Facture Zone (N2), and mid plate (N5).

The prototype design for the RSN water-column moorings envisions four groups of sensors, some on fixed platforms and some associated with profilers, to provide measurements through the entire water column. The design comprises an EOM cable anchored to the seafloor, rising to a buoyant platform 200 m below the surface. Sensors on the 200-m platform provide continuous measurements at this fixed point in the water column. An instrumented profiler samples ocean conditions from the seafloor to the platform depth by moving up and down the EOM cable. Another set of fixed instruments will be deployed at the mooring base on the seafloor. Finally, a winch on the platform enables an instrumented profiler to record conditions between 200 m and the sea surface. This highly capable mooring concept will rely upon engineering for robustness, lifecycle planning, and effective maintenance.

At the RSN, sensors will provide a baseline capability, but by no means a complete or exhaustive capacity. Future investigators will bring funded experiments or campaign measurements to the research platform to exploit its multidisciplinary potential. The Monterey Accelerated Research System (MARS), a single-node cabled observatory at 890 m in the Monterey Canyon, funded in part as a testbed for the OOI, is already attracting requests from domestic and international users (26).

The following is a brief summary of the five primary RSN node sites. All sites will host an initial suite of basic sensors, most likely an ocean bottom seismometer coupled to a hydrophone, a differential pressure gauge, a pressure sensor, and a current meter. N1 and N3 will additionally host the water column moorings discussed above. Further initial instrumentation suites specific to science topics at specific nodes are summarized below.

Node 1: Hydrate Ridge

Node 1 is a focus for numerous interdisciplinary studies that address process linkages associated with gas hydrate formation, the flow of carbon from the crust and from the coast to the deep sea, and the connections between biogeochemical processes and climate change in a zone of high biological productivity. Hydrate Ridge was the site of Ocean Drilling Program (ODP) Legs 146 (Site 892) and 204 (Site 1249). RSN cabled infrastructure at this site includes over 200 km of backbone cable and two secondary nodes, NP-1 (900-m water depth) and NP-2 (500-m water depth). NP-1 provides access to the gas hydrate site via two low-voltage nodes for future experiments and NP-2 is the cable connection to the Pacific Northwest Endurance Array (see Coastal-Scale Nodes).

Node 2: Blanco Transform Fault

Cabled infrastructure at the Blanco Transform Fault represents the best opportunity within the RSN for capturing large earthquakes, and examining deformation at a transform plate boundary and its relation to deformation and seismicity mid plate, at the subduction zone, and at the spreading center. The cable is required for this experiment to provide real-time observations of the impact of seismic events at the other nodes as events unfold. A daisy-chained array of eight medium-voltage nodes and ~ 100 km of extension cable provide access to a suite of broadband seismometers at the Blanco Ridge.

Node 3: Axial Seamount

As confirmed in more than two decades of interdisciplinary studies, Axial Seamount is seismically, volcanically, and hydrothermally active, having erupted at least three times in the last 12 years. Infrastructure includes the backbone high-voltage node (N3), well away from recent eruptions, a low-voltage node that provides communication to the core suite of geophysical instruments, and a 40-km extension cable connecting to a secondary node located on the southeast summit flank providing access to the ASHES vent field and the caldera. A series of five low-voltage nodes and six medium-voltage junction boxes will support a diverse array of core sensors designed to examine linkages among seismic activity, summit inflation, hydrothermal flow, fluid chemistry, and microbial output and temporal changes in assemblages.

Node 4: Subduction Zone

Science at this site is focused on earthquake and tsunami generation, plate-scale strain, and hydrological connectivity. The Cascadia subduction zone generated a magnitude 9+ earthquake in 1700, causing a large tsunami that was recorded in Japan. Correlations between fore-arc basin structure and the slip history of large earthquakes will inform the design of a future seismic and geodetic network at this node. In addition to the core geophysical sensors at the backbone node, the site currently hosts 40 km of extension cable and a low-voltage node upslope to the east to support a suite of core geophysical instruments. The water column mooring at this location would provide observations in the “upstream” California Current and along-shelf gradients of properties with respect to the Newport Line (see discussion of Coastal-Scale Node).

Node 5: Mid-Plate

The mid-plate Node 5, located between Axial Seamount and the Pacific City shore station, provides a reference site that will allow study of stress propagation through the plate, as well as intraplate deformation and its relation to plate boundary failure. This site will allow future water column study of the subtropical gyre and will provide insights into seasonal, interannual, and interdecadal climate change and the impact of these changes on regional physics and ecology. The mid-plate node serves as an important site for studying the flux of carbon from the shelf across the slope to deep water.

D. Coastal-Scale Nodes (CSN)

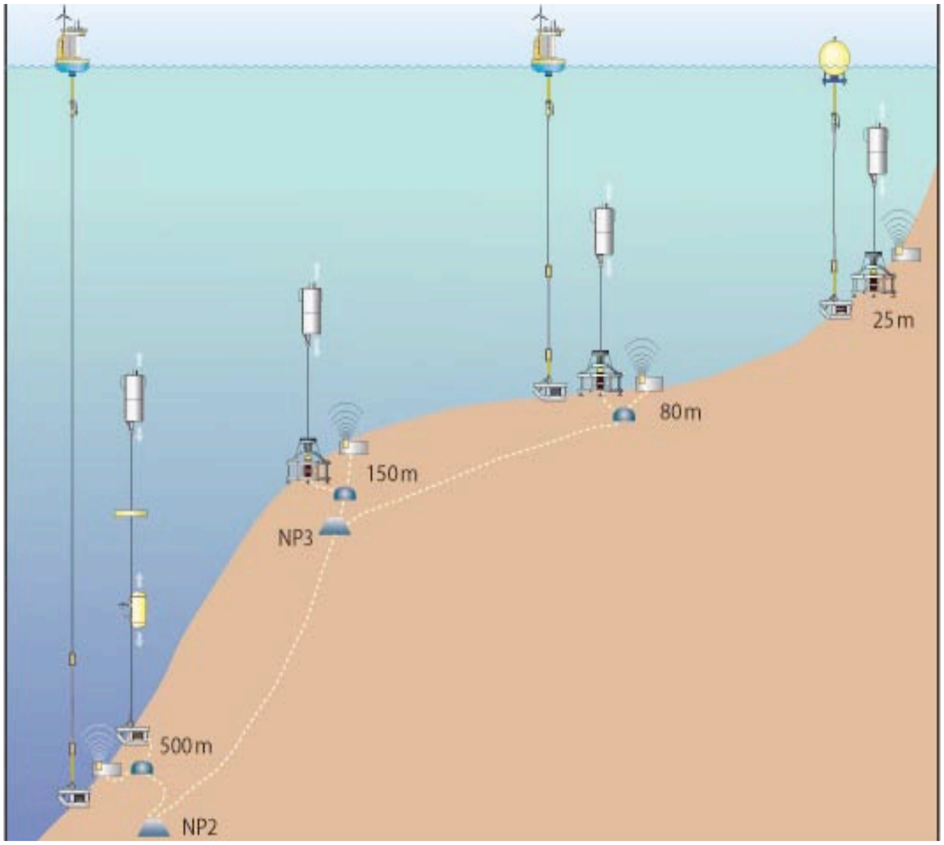
The coastal zone, with heat, nutrient, and saline fluxes, mass input, and topographical changes, plays a critical role in ocean physics, ecology, and biogeochemistry, and it is where human impact is felt most strongly. Yet, the coastal ocean is undersampled in space and time and across a range of physical, chemical, and biological variables. Sustaining an advanced observing capability in coastal waters remains a challenge. The OOI’s Coastal-Scale Nodes (CSN) fill this gap by providing sustained, but adaptable, access to complex coastal systems. Deploying and replicating the CSN infrastructure along the U.S. coasts in the coming decades will transform our observing capabilities and understanding of the coastal ocean.

The initial stage of the coastal observatory consists of two elements: a long-term Endurance Array off the Pacific Northwest and a relocatable Pioneer Array in the Middle Atlantic Bight. The Endurance Array is a long-term observatory of moored and mobile assets deployed across the continental shelf and slope to provide continuous observations at key locations, documenting episodic events and longer-term changes. The Endurance Array will complement existing and planned observatory and infrastructure in the region. The Pioneer Array will provide a more detailed, three-dimensional view of key biophysical interactions at the shelf break using a flexible, multiplatform array combining moored and mobile assets with high spatial and temporal resolution. With its initial location south of Cape Cod, the Pioneer Array will be embedded in existing coastal observing assets, including National Data Buoy Center (NDBC) weather buoys, and will be supplemented by a $10M hardware investment from the Commonwealth of Massachusetts.

Endurance Array

The coastal ocean off Oregon and Washington is characterized by a relatively narrow shelf, an energetic eastern boundary current, persistent wind-driven upwelling, a large buoyancy source (fresh water from the Columbia River), a number of distinct biogeographical regimes, mesoscale variability forced by bathymetry and fluid dynamical instabilities, and interannual variability forced by fluctuations in the tropical Pacific (e.g., El Niño Southern Oscillation), as well as variations in the large-scale circulation of the North Pacific (e.g., Pacific Decadal Oscillation). Over this shelf, water properties and biological community size and composition vary most strongly in the cross-shelf direction. A well-instrumented array spanning the continental shelf is key to sorting out ecosystem response across this strong gradient.

The Endurance Array will comprise lines of mooring, one located off the coast of central Oregon (Newport Hydrographic Line) and a second at a contrasting site in central Washington (Grays Harbor Line), north of the mouth of the Columbia River (Fig 2). The array of surface and subsurface moorings deployed off Newport, Oregon (44° 39'N) (Figure 6), has targeted sites with water depths of approximately 25, 50, 80, 150, and 500 m. Moorings off of Grays Harbor (47°N) will be at 25, 80, and 150 m depths (Figure 7). Moorings will be maintained at as many sites as funding allows, listed in priority order, starting with the highest: Oregon 80 m, Oregon 25 m, Oregon 500 m, Washington 80 m, Washington 25 m, Oregon 150 m, Washington 150m, and Oregon 50m. Vertical profiling moorings will provide long-term observations of shelf processes, extending from the air-sea interface through the water column to the bottom, and benthic instrumentation packages or nodes will provide sampling on and near the seafloor. Profiling moorings and benthic nodes will be cabled and connected to the backbone cable of the RSN at the 80, 150, and 500 m sites on the Oregon line. Moorings and benthic instruments at the 25 and 50 m sites will be stand alone. Surface moorings will be located at 25, 80, and 500 m sites; these would not be cabled but would generate power, support two-way telemetry, and provide power and a data link to the bottom with EM cable. The surface moorings will also have acoustic links to nearby subsurface moorings and thus to the RSN.



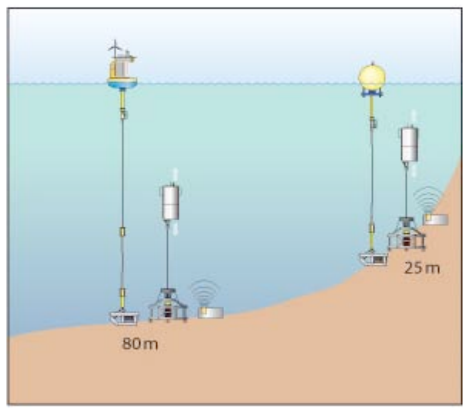


Figure 6. The Oregon line of the Pacific Northwest Endurance Array. Note that the 50-m mooring, which has the lowest priority, is not shown. Attachments to the RSN cable, and the location of surface moorings and subsurface profiler moorings, are drawn in.

Figure 7. The Washington line, showing the 25-and 80-m sites, which have higher priority than the 150-m site.

The surface moorings, except at 25 m, will provide the capability to collect surface meteorology and air-sea flux data and will support high-power, high-bandwidth, multidisciplinary science instrumentation in the buoy well and at 5 m beneath the surface. At the 25-m site, the surface buoy will be smaller and hardened against submergence by breaking waves. Fixed sensors will be placed along the mooring lines below surface moorings to provide high-resolution time series.

Vertical profiling moorings will carry multidisciplinary core sensor suites, and the profilers will have additional payload and power capacity for future sensor additions. With connection to the RSN cable, vertical profiles can be made continuously. All profilers are winched to the surface with the exception of the deep-ocean profiler at the 500-m site. Profilers not attached to the cable would draw from a bottom-mounted battery reservoir and be capable of profiling many times per day for six months.

Medium-voltage benthic junction boxes at the nodes tied in to the RSN cable (80- and 500-m isobaths) will support high-power, high-bandwidth instruments with interactive, real-time communications. The autonomous mooring at the 25-m isobath will support a low-voltage benthic junction box. A multidisciplinary benthic instrument package will be deployed to sample the bottom boundary layer. Where the benthic sensor package is hooked to the cable, high power and bandwidth will enable the construction of benthic laboratories.

Autonomous underwater gliders will also carry multidisciplinary sensor suites. Measurements will be obtained with submeter vertical resolution on missions that range from one to six months. The glider array will sample both across-shelf lines and north-south seaward lines totaling approximately 500 km in length.

Pioneer Array

The Middle Atlantic Bight (MAB) of eastern North America is characterized by a relatively broad shelf, a persistent equator-ward current originating from the north, a well-defined shelf-break front separating shelf and slope waters, distributed buoyancy inputs from rivers, variable wind forcing, and intermittent offshore forcing by Gulf Stream rings and meanders. The MAB Pioneer Array (Figure 8) is designed to resolve transport processes and ecosystem dynamics

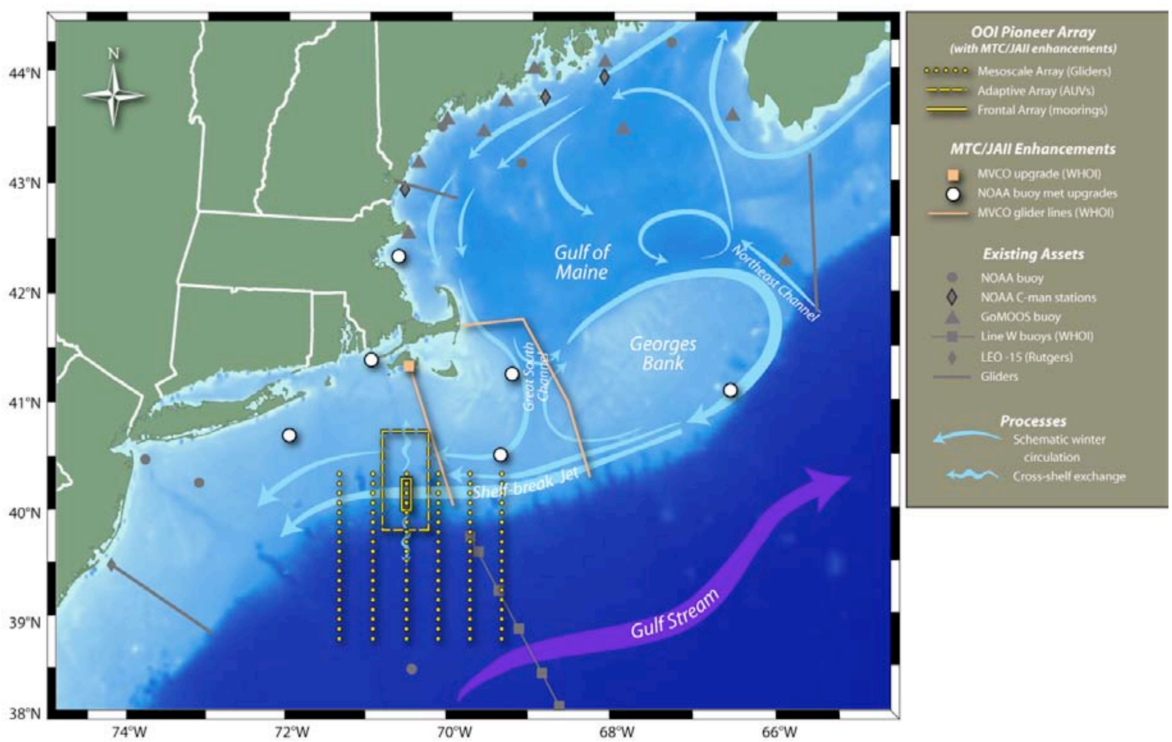


Figure 8. Plan view of the multiscale Pioneer Array in the context of other regional observing elements. A moored array will be centered at the shelf break front and jet south of Cape Cod, MA, AUVs will sample the frontal region near the moored array, and gliders will resolve mesoscale features on the outer shelf and the slope sea between the shelf break front and the Gulf Stream.

within the shelf-slope front, which is a region of complex dynamics, intense mesoscale variability, and enhanced biological productivity. It will collect high-resolution, multi-disciplinary, synoptic measurements spanning the shelf break on horizontal scales from a few kilometers to several hundred kilometers. In contrast to the Endurance Array, the Pioneer Array will be able to be moved to a new location to compare and contrast different shelf-break systems. Current budget planning would allow relocation every three years.

The Pioneer Array will employ surface moorings, subsurface profiler moorings, gliders, and AUVs to sample on multiple horizontal scales from the air-sea interface to the seafloor (Figure 9). The moored array will extend 40 km across the shelf, centered at the climatological location of the shelf-break front. The Pioneer Array will include four surface moorings able to be equipped to measure surface meteorology and air-sea fluxes, fitted with power generation capability, and moored with EM cable to the seafloor, allowing incorporation of a benthic node for science user instrumentation. Two EM moorings will incorporate AUV docking stations near their bases to recharge batteries, offload and store AUV data, and transfer commands. AUVs will run user-controllable missions surrounding the moored array, extending coverage of the frontal region to 100–200 km along and across shelf. Eight additional moorings will support water column profilers. A fleet of six or more gliders will sample the mesoscale field within a region of about 300 x 300 km in the slope water offshore of the moored array.

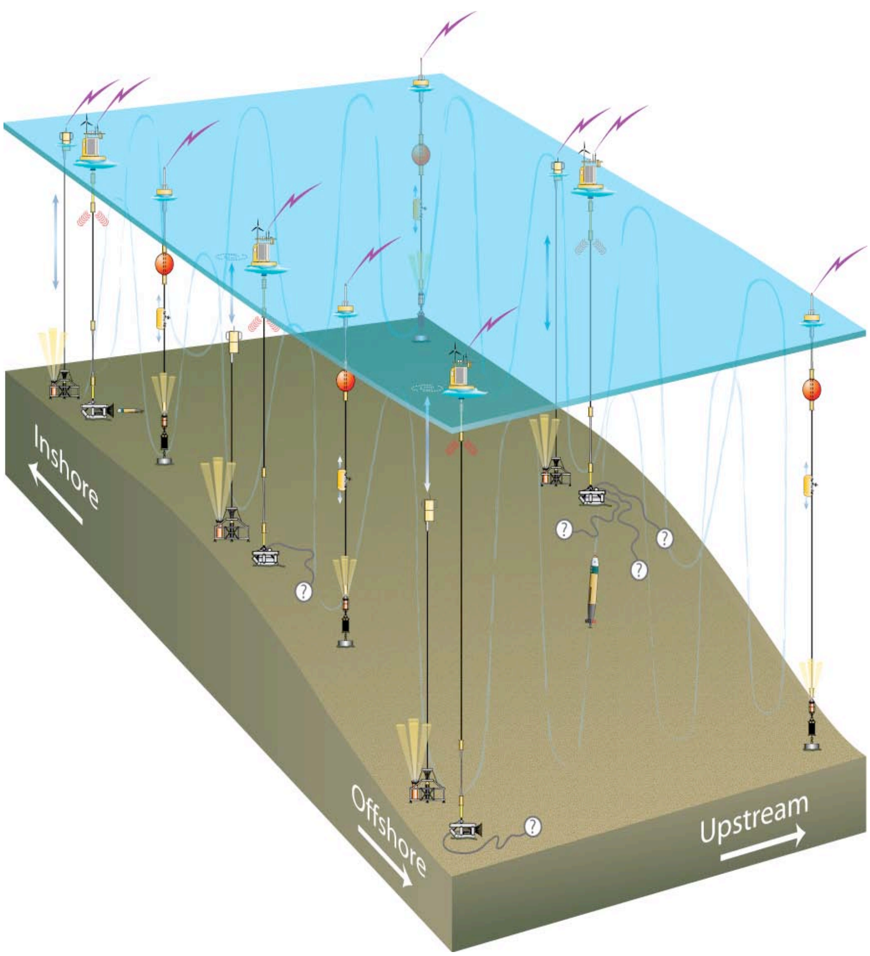


Figure 9. Schematic diagram of the Pioneer Array, showing EM surface moorings, profiler moorings, AUV docks (at the base of inshore and offshore EM moorings), multi-function nodes (MFNs) for science user instrumentation (at the base of central EM moorings), and AUV transects in the vicinity of the moored array. Glider transects are not shown in this view.

The Pioneer EM moorings will share their surface buoy design, and most of their subsurface mechanical design, with the Endurance Array. The surface buoys will provide 50–100 W of power, Ethernet and acoustic communication with subsurface sensors, and three different types of airside communication systems (Iridium, FreeWave, and WiFi). The development of a more capable surface buoy will be shared with the OOI's Global-Scale Nodes.

Profiler moorings will be of two types. The first will be a surface piercing, winched profiler design shared with the Endurance array. There will be four of these, paired with the four EM surface moorings. The other four profiler moorings will be of conventional design, equipped with a wire-crawler type profiler that will sample all but the upper 15 m of the water column and an Acoustic Doppler Current Profiler (ADCP) situated near the bottom. The profilers and ADCPs are the primary tools for collecting time series in the water column, providing interdisciplinary observations resolving the semi-diurnal tidal band and longer periods. These observations will be supplemented by multidisciplinary sensor packages at fixed depths on the EM moorings to capture the near-surface and near-bottom part of the water column. Instruments on both types of profiler will transmit data to shore via Iridium modem, which will also permit command and control from shore. The profiler and ADCP will be powered from internal battery packs. The candidate profiler is capable of approximately one million meters of travel, allowing six profiles per day for a year in 500 m of water. The ADCP, with ancillary battery packs, will be capable of greater than one profile per hour for a year.

The Pioneer Array will include four multifunction nodes (MFNs), benthic platforms at the base of EM moorings that will supply communications and power. The MFN power system is geared towards a single client with large, episodic power requirements such as an AUV, but will also support multiple, lower power instrumentation for investigator-supplied sensors. AUVs will be used to study cross- and along-front "eddy fluxes" due to frontal instabilities, wind forcing, and mesoscale variability, with the glider array surveying the outer shelf and slope around the moored array to resolve features of the Gulf Stream as they impinge on the shelf break front. The AUVs and gliders will carry a multidisciplinary sensor payload similar to the Endurance gliders. Additionally, each AUV will be outfitted with a novel, reagent-based nutrient sensor providing nitrate, phosphate, and silicate measurements. Two AUVs will run repeat missions near the moored array. The expected interval between missions for a 50–100 W EM mooring is 7–10 days. The third AUV will be deployed periodically (e.g., monthly) from a small vessel and subsequently recovered from that vessel, allowing freshly calibrated sensors to do a comparison check on the quasi-permanent sensors on the moorings and the continuously deployed AUVs. Repeat glider missions will last for several months until the instruments are recovered for servicing and replaced by another set.

SECTION 4: Making a Difference

The OOI will engage a wide swath of the ocean community, from individual investigators using the infrastructure, to distributed groups of scientists using mainly real-time streaming data, to a growing network of informal and formal educators, to the general public who are interested in the ocean. This last group will be very large given that other smaller ocean observatories now receive upwards of 250,000 Web hits per day, of which more than 70% are from the general public.

This section highlights different aspects of how the OOI might be used by the ocean community in a series of use-case scenarios. These use-case scenarios are followed by a section highlighting education and outreach partnerships as well as potential interagency and international collaborations that will be enabled by the OOI, which represent a significant NSF contribution to the Global Earth Observing System of Systems (GEOSS). A third section describes how the introduction of OOI technologies will change the ways in which ocean scientists will conduct research, some in ways not yet imagined.

A. Use-Case Scenarios

Use-Case Scenario: Using OOI Real-Time Data in a Museum Exhibit

A major metropolitan science center, which averages 1.5 million visitors a year, is developing an exhibit on storm impacts to coastal ecosystems. It has decided to highlight the physics of storms, how the oceans play a central role in storm intensity. The science center also wants to highlight how storms mix the ocean, which directly impacts the overall productivity of the ocean. One highlight of the exhibit is that visitors are able to watch the oceans change during the storms in real-time on a large video display prominently featured in the exhibit. Needing a link to real-time data, the center's Director of Public Programs approaches OOI education staff to request region-specific information on related observatory-enabled research. OOI education staff, knowledgeable about free-choice learning environments, work with science center staff to provide the information needed to produce: (1) current, customizable maps of deployed mobile platforms and moored system data streams; (2) to complement the real-time data streams simplified schematic representations of sensors that explain what data are being collected; (3) contextual information that explains, in public-friendly terms, the physics and associated biological responses; and (4) and relevant interactive, online, inquiry-based, standards-aligned, teacher-tested activities to be used during teacher professional development workshops in conjunction with the new exhibition. The OOI provides backbone support to this high-visibility component to the outreach project because its high bandwidth allows real-time data from coastal ocean being impacted by storms. Additionally, the integrating reach of the OOI CI allows aggregation of other NOAA and NASA data streams that complement the exhibit.

Use-Case Scenario: Ecosystem Management

A group of NOAA and university researchers are conducting a series of modeling studies of the transport and migration of fish along the eastern seaboard. The timing and migration patterns of higher trophic levels are strongly influenced by the structure of water column physical and chemical properties; unfortunately, the uncertainty in the regional hydrography directly impacts the efficacy of fisheries management approaches based on marine protected areas, no fishing areas, marine reserves, and rotating closures. These modelers are focused on developing the observational and modeling frameworks for nowcasting and forecasting of regional hydrography to facilitate analysis of the movement of water masses and their associated populations. Their goal is to assess model predictive skill and understand what underlies the variability in the skill assessments across the models. Does the variability reflect differences in model parameterizations or differences in model complexity, or do the differences reflect different fundamental assumptions within each of the model frameworks? Because this research requires in-water data, the researchers begin their effort by entering the OOI easy-to-navigate CI Web portal. They use the OOI CI data system to subscribe to real-time OOI data streams, as well as NOAA and NASA remote-sensing and shore-based radar network data. This CI capability provides the modelers with a wonderful horizontal and *in situ* data coverage. During the ensemble of model runs that are assimilating data, the researchers realize that they are having a particularly hard time in modeling the shelf-slope front. Given that the OOI CI allows for two-way interactivity between the shore-based researchers and the in-water assets, the researchers establish a near-real-time workflow to adjust glider and AUV sampling to collect high-resolution data in regions where the models have largest disagreement among the different models. The researchers are then able to assess which model was providing the accurate forecast of the ocean. This focuses the researcher to begin examining hypotheses about why certain models worked better then others providing fundamental insights into the ocean system.

Use-Case Scenario: PI Installation of a Sensor on the OOI Network

A seismologist, Mike Williams, from the University of Glide in Oregon has been actively involved in the EarthScope project where strainmeters recently detected episodic tremor and slip events along the Cascadia subduction zone beneath Washington. He is interested in far-field triggering of earthquakes and stress propagation. Mike wants to extend his investigations into the marine environment to determine whether earthquakes on the Juan de Fuca Ridge and at mid-plate locations are related to these Cascadia events. The seismologist explores the JOI Division's OOI Web pages, which direct him to an interactive online "how to" manual that provides NSF proposal requirements, costs related to infrastructure components (e.g., extension cables, connectors, ROV day rates), links to up-to-date node-engineering reports, including controls that should be exposed for *in situ* manipulation, experiment scheduling, and user examples to help guide him through experimental design and proposal submittal. The site also includes a checklist of required information, such as sensor and interface (power and network) specifications;

calibration, maintenance, and decommissioning needs; sensor frequencies; sparing philosophy; and possible educational products. The Web pages list contact information for engineering-CI help and initial guidance from a project scientist. Early discussions among Mike, NSF, and the RSN indicate that there will not be any substantial Navy concerns regarding security issues. Mike successfully submits all required information, his proposal is well reviewed by NSF panel(s), and his proposal is funded.

Following the award, Mike meets with engineers, an RSN project scientist, and a CI representative to finalize milestones, which may include sensor calibration and testing (likely in a vault for a broadband seismometer), full metadata completion on the sensor, data products, maintenance and installation schedules, and sensor qualification. OOI reporting systems ensure that the project stays on schedule, risks are assessed, and problems are highlighted early. Following qualification, the broadband seismometer is ready for deployment. During deployment, OOI obtains detailed site information, the operations center and the CI test facility confirms the instrument is functioning properly, and, for each sensor deployed, scientists aboard the ship complete a report that contains sensor locations and associated environmental data. These online reports are compiled at the end of each installation cruise. Subsequent to successful installation, data flows through the CI infrastructure in real time to Mike Williams and the global community. At the end of the experiment, the sensor is recovered and decommissioned. The RSN and Mike provide a final report to the OOI facility operations committee and to NSF.

Use-Case Scenario: Exploring the "Oceanic Genome"

A group of researchers has employed genomic sequencing techniques to provide a glimpse into the metabolic function and genomic potential of microorganisms found in the upper ocean. They are now poised to determine what species, genes, and metabolic processes modulate particular biochemical transformations under different environmental conditions. However, this requires collection of discrete samples at multiple locations synoptically and in time-series fashion to capture microbial populations as they experience different physical and chemical forcing. Approaching this problem using ship-based operations is fraught with numerous logistical and practical constraints, so the team has devised an instrument for collecting and preserving samples *in situ*. The sample-collection devices are placed on moored vertical profilers and can be dynamically positioned throughout the upper water column for deployments lasting up to one year. The number of sample-collection events is limited and it not possible to know *a priori* when and at what depth exactly samples should be taken. Instead, the researchers must rely on information gleaned from a distributed set of sensors and models to predict when ocean conditions are appropriate for their collections. The CI allows them to employ a shoreside event-scheduling algorithm to monitor the incoming data and model outputs, and then relay appropriate sampling commands to the samplers over time. Sensors attached to the profilers help fine tune the depth of the samplers so as to maximize chances of positioning the water intake within the feature of interest. During the course of the experiment, the team anticipates a need to reposition gliders and AUVs to help refine contextual data as well as tune and test models that are critical for determining when and where samples should be obtained.

B. Partnerships

Because the OOI will enable sustained and configurable observations of remote ocean environments, it will provide the foundation for numerous, substantial partnerships and collaborations. OOI infrastructure and core capabilities will make possible the detailed scientific observation of short-term, energetic processes and longer term subtle changes that might approach or trigger “tipping points” in planetary phenomena of interest to scientists or society. Examples include global climate and major earthquakes, which are of great interest to mission agencies and private industry. The OOI cyberinfrastructure will ease access to the network’s real-time data as well as data in third-party archives to support analyses and modeling. Here we highlight only a few partnership examples, representing the spectrum of potential interactions.

Within NSF, the EarthScope project, which is devoted to understanding the deformation and evolution of the North American continent and underlying mantle, will dovetail both practically and intellectually with OOI’s Regional Scale Nodes on the Juan de Fuca tectonic plate, which is controlling the deformation of the Pacific Northwest and the earthquake rupture along the Cascadia Subduction Zone. The Directorate for Biological Sciences’ National Ecological Observing Network (NEON) will use distributed sensors to understand complex, diverse land habitats in the U.S. and will monitor baseline environmental parameters such as temperature, pollutant and trace concentrations, aerosols, and biological productivity on land and in the atmosphere that can tie in OOI’s observations. The NSF Office of Cyberinfrastructure is committed to empowering all aspects of computation and networking necessary to implement many of the developing data-driven environmental programs, and is particularly interested in exploring commonalities among these three large distributed sensor network facilities.

The mission agencies NOAA and NASA will also develop partnerships with the OOI in a number of ways. NOAA is the lead agency for the Integrated Ocean Observing System (IOOS), an operationally oriented approach to ocean observing intended to serve societal and national needs. The OOI will directly contribute to IOOS through the development of novel observing, data assimilation, and data management techniques as well as by advancing understanding of ocean phenomena upon which accurate predictions and forecasts important to society depend. Through NOAA support, the cyberinfrastructures for OOI and IOOS will converge to enhance interoperability of these two national systems, over time. IOOS, in turn, will contribute to the OOI effort by supporting a broadly distributed set of core observations, which will provide context in which the interactive, detailed OOI experiments can be posed. In reciprocity, OOI’s science-driven observations and experiments can be integrated into the suite of observations available to NOAA and IOOS. NASA is committed to studying climate change and life on other planets. By illuminating unexplored ocean environments, the OOI will be involved in cutting-edge science on both fronts. NASA's Tracking Data Relay Satellite System (TDRSS) may be invaluable to the OOI for large-volume data collection from coastal and global buoys. We expect that NASA scientists and technologists will be working closely with us by the time the OOI system is in the water.

The U.S. Navy has contributed a great deal to the technologies and methodologies being integrated into the OOI. Examples include the development of mobile platforms (AUVs and gliders), research ships, and command/control of remote systems. The OOI, in turn, will provide data and knowledge essential to operations in the world ocean. The Navy's historical responsibility for ensuring freedom of the seas will depend increasingly upon access to oceanographic data, information, and global predictions. This has lead to the development of the Littoral Battlespace Sensing, Fusion, and Integration (LBSF&I) program to transition observatory technologies into relocatable networks that will support the Pacific and Atlantic fleets.

Strong formal and informal connections with other sovereign coastal nations interested in interacting with the oceans have evolved over the past decade. For example, the Canadian initiatives, NEPTUNE Canada and the associated VENUS program, are already implementing cabled observatories on regional and coastal scales off North America. Scientists at Canada's Department of Fisheries and Oceans, as well as university researchers in the Pacific Northwest, are interested in Ocean Weather Station Papa and integrating observing efforts over the region. The European Seafloor Observatory Network (ESONET) is somewhat more application-oriented than the OOI, but much of their technology is similar and we expect to develop stronger relationships with them. European ocean time-series sampling (EuroSITES) shares an interest in the Irminger Sea, and a coordinated effort there could link the Global-Scale Nodes to this emerging network. The international time-series group, OceanSITES, provides a framework for building global partnerships focused on open-ocean time-series observatories. Japan, through its ARENA (Advanced Real-time Earth monitoring Network in the Area) Program, is developing cabled seafloor observatories whose central focus is geophysics and dynamics. This program's research priorities include advancing understanding of ocean circulation, hydrates, hydrothermal fluxes, marine fisheries and mammals, and deep-sea microbiology. China, Korea, Singapore, South Africa, Australia and several Persian Gulf states, are all developing similar programs focused on their coastal and offshore resources. OOI will be seeking ways to fruitfully interact with them.

At the multinational level, the Group on Earth Observations (GEO) includes 71 member countries, the European Commission, and 46 participating organizations working together to coordinate a Global Earth Observation System of Systems (GEOSS) from existing or new Earth-observing systems. This global community is focused on a future wherein decisions and actions for the benefit of mankind are informed by coordinated, comprehensive, and sustained Earth observations and information. The OOI Network's advanced capabilities will play a critical role in supplying data, information technology, and knowledge for this global effort.

OOI efforts will take advantage of existing partnerships in formal and informal education, and grow others as adaptive and continuous access to remote parts of the ocean becomes a normal part of the learning environment. The program already has strong existing ties with education centers —for example, the marine educators at the OOI implementation institutions are closely involved with several Centers for Ocean Sciences Education Excellence (COSEE). The anticipated new COSEE Networked Ocean World will be a valuable resource as the OOI develops to study and implement education methods specifically tailored to use ocean observing systems. Partnerships will also be formed with museums and aquaria, by collaborations with regional TV stations, and by educational Web sites, growing out from those that are already working with the implementing partners. While the OOI cyberinfrastructure assets will be used to develop a common technical Web site to facilitate the emerging education infrastructure, the program will also emphasize outlets with large existing audiences (e.g., whyville.net, Second Life, UCSD-TV) rather than only creating new ones. Broad goals have been identified for education activities associated with the OOI. They will: have a nationwide impact; enhance the size, intellectual scope, diversity, and sophistication of the ocean education user community; emphasize the creative opportunities enabled by novel aspects of the OOI; develop partnerships among scientists, formal and informal science educators, and technology specialists in ways that will extend the impact of OOI accomplishments most effectively; and promote a culture of open access to OOI assets for the broadest set of audiences and partnerships so that the most creative ideas come forward and are fully developed.

Corporate partners will become increasingly important in the overall program at a variety of levels. Successful construction of the OOI will require the expertise and support of highly capable private-sector management and financial planning scenarios that are necessary to implement large and complex programs, including design, construction, and operations. Technip, a major infrastructure supplier to the oil industry, will play a large and critical role in the funding, development, and construction of the Extended Draft Platform for the OOI Global-Scale Nodes. The oil industry, which is moving rapidly toward drilling the outer continental shelves in its quest for oil and gas, is focusing on sea operations over the next decade. It will require many of the capabilities being developed in the OOI to routinely drill, operate, and produce from the outer continental shelf.

C. Disruptive Technologies

As defined in Wikipedia, a "disruptive" technology is a technological innovation, product, or service that eventually overturns the existing dominant technology or status quo product in the market. A disruptive technology comes to dominate a field by either filling a role that the older technology could not fill (as more expensive, lower-capacity but smaller-sized hard disks did for notebook computers in the 1980s) or by successive performance improvement that finally displaces an existing technological standard (as digital photography has begun to replace film photography). The concept shares many similarities with biological evolution. The OOI's permanent observing presence in previously uninstrumented locations is an example of the first type—filling the unfulfilled market niche. Its interactive cyberinfrastructure is an example of the second type—displacing the existing standard of a normal data download and distribution system.

The Internet today is vastly different than the Internet of five years ago and the changes that will be evident five years from now, when the OOI has been installed, are nearly unpredictable. The quality and degree of adoption of the Internet today greatly exceeds its state in 2002. Much of this progress is based on the exponential growth in capabilities of consumer electronics and information technology. For example, the number of transistors on a square centimeter of silicon will continue to double every 18 months, the density of disk storage will double every year, and network bandwidth will double every eight months. Today's desktop 2 TB RAID will be 64 TB and the 10 Gbps RCN fiber optical connection will be running at 1.8 Tbps. The same exponential behavior characterizes the future of genome sequencing. The first two sequences of composites of individuals' genes cost tens of millions of dollars in 2001; a more accurate human genome has just been published at a cost on the order of $100,000 (27), and the X Prize for Genomics is offering $10M to the first successful sequencing of a human genome for $1,000 (28). Major advances in technology that are broadly viewed as "disruptive" or revolutionary rather than evolutionary will often depend upon the exploitation of exponential expansions in capability.

Major changes in business models, forced in part by disruptive technologies including software, have lead to a major transformation from closed to open systems and ideas of virtualization. These provide new opportunities for the OOI. Proprietary operating systems attached to computer manufacturers are increasingly rare—the growth of LINUX over the last five years is an excellent example. *Virtualization* has become a dominant principle in networking, computing and storage including the concept of grids that integrate all three of these information technologies. Amazon's Elastic Compute Cloud (29) that makes available virtual machines to users on a demand basis is vastly different than today's supercomputer centers that continue to rely upon the idea of batch processes and static, stored files; it's now easier to get more free storage in a Google™ Mail account than most universities provide to their students or faculty. The question today becomes where to buy most reliable bytes for the buck, rather than how to build and maintain an independent storage system. Driven by economics, most users may eschew infrastructure investment in favor of a business arrangement with a second-party provider within a decade.

The OOI is building its cyberinfrastructure on many of these concepts, especially virtualization. The OOI concept of data streaming to users in near-real time is a major departure from science's current file-based, archival approach to research and discovery. Streaming will provide timely information that will enable user-moderated or, more interestingly, machine-to-machine control of the sensors, actuators and network itself. Not every engineer or developer is a great knowledge networker. The OOI cyberinfrastructure will make it possible for good ideas about open data to be circulated widely to take full advantage of collaborative thinking. This collaborative interaction enabled by the cyberinfrastructure will allow many to contribute to the observatory in order to shape and share its future. This social or knowledge networking is a collective matchmaking device across diverse scientific communities that will, perforce, increase rapidly the size of the oceanographic community.

The exponential changes in genome sequencing can have a very disruptive impact on understanding the microbial biology and ecology of the oceans. Only a small percentage of the species have been identified at this stage, but the organisms themselves vary in abundance based on location and physical conditions, such as temperature and salinity, that vary seasonally as well as in response to climate variability on longer time scales. The rapid changes in the technology make it possible to imagine a remote, observatory instrument that can provide real constraints on these variations and, at once, make a leap from primitive instruments that measure proxies for species (e.g., presence of a toxin) to a full understanding of the impact of change on microbial ecology, the bulk of life in the oceans. The OOI is planning now to build a network capable of supporting such instruments in 5–10 years' time including adequate power for supplying seawater, cleaning protocols, computation, and bandwidth for returning data and allowing remote manipulation.

Facilities such as the OOI, supported with funds from the MREFC account, were introduced to engender major advances in scientific fields. Transformational progress is not achieved through incremental change, but by embracing technologies that are demonstrating exponential growth or which introduce major changes in the way measurements are made at sea. For example, naval architecture has introduced incremental improvements in expeditionary oceanography, whereas major changes have come about through new approaches to determining position (e.g., GPS with at-sea accuracies better than tens of centimeters) and communications (e.g., HiSeasNet). It is impossible today to think of going to sea without these capabilities, both very new concepts in the history of oceanography. The OOI will introduce the same kinds of disruptive technologies in order to succeed and spark the imaginations of a new generation of oceanographers.

SECTION 5: Project Management and Implementation

A. JOI, Implementing Organizations, and the Consortium for Ocean Leadership

Beginning in 2004, the National Science Foundation established a project office at the Joint Oceanographic Institutions (JOI) to take responsibility for coordinating planning for the OOI. JOI, a not-for-profit consortium of more than 30 member academic institutions with graduate programs in marine geophysics and oceanography, recently merged with its sister organization, Consortium for Oceanographic Research and Education (CORE), to become the new Consortium for Ocean Leadership. Both former organizations, now divisions within the Consortium for Ocean Leadership, have relevant experience in large multidisciplinary science, education, and facility operation programs. JOI for decades managed international scientific ocean drilling programs for NSF, and the division is currently completing a $130M project for NSF's Ocean Sciences Division, supported with funds from the MREFC account, to deliver an upgraded U.S. Scientific Ocean Drilling Vessel. CORE has historically facilitated policy, research, and education forums, such as the National Ocean Partnership Program (NOPP), the National Ocean Sciences Bowl, and the Census of Marine Life.

In calendar year 2007, using a competitive acquisition process, the JOI Division made awards to three partners to lead the final OOI design and implementation. Following guidance from its advisory structure and NSF, the JOI Division required the lead partners, known as "implementing organizations," or IOs, to be academic institutions to ensure that the project team retained community expertise from the planning phase. The University of California San Diego (UCSD) will implement the OOI cyberinfrastructure component with several other academic and industry partners. A consortium of Woods Hole Oceanographic Institution (WHOI), Scripps Institution of Oceanography, and Oregon State University (OSU), along with several significant industry partners, will implement the Coastal- and Global-Scale Nodes. The University of Washington (UW) will implement the Regional-Scale Nodes. Additionally, the MARS (Monterey Accelerated Research System) cabled system, installed by the Monterey Bay Aquarium Research Institute (MBARI) with support from NSF's Ocean Technology and Interdisciplinary Coordination program, has a formal role in the OOI as the program's testbed facility. Each partner brings to bear a comprehensive skill set and select domain expertise in ocean research and engineering. Each partner also has related programs in research and formal and informal education, and ties with industry, regional and state governments, and other federal agency research programs, that can be leveraged to increase OOI outcomes.

Working with NSF via a Cooperative Agreement, the Consortium for Ocean Leadership with its major partners UW, UCSD, and the WHOI/Scripps/OSU consortium will form an integrated project team to implement the OOI facility on behalf of the community. Part of this team's role is to develop an operational framework, in consultation with the program's advisory structure and NSF (and perhaps other potential future sponsors), that anticipates the full spectrum of users, and ensures a professionally managed and smoothly operating research facility. The team also must manage program risk, apply best practices in engineering and project management, and deliver a transformational facility within the constraints of the allocated budget and MREFC account process. Additionally, the project team will pursue the Consortium for Ocean Leadership's wider organizational goals in the context of the OOI: catalyzing the creation of new knowledge and understanding, encouraging the development of new research avenues through partnerships with other disciplines, building connections between ocean observing and other national and international science initiatives, developing a fresh generation of ocean leaders, and helping to create an ocean literate society.

B. Advice, Review, and Governance

A formal volunteer advisory structure, comprising approximately 80 individuals on six standing committees, carried out large parts of OOI's planning and initial design process, from 2004 through the issuance of the Conceptual Network Design and its revision in March 2007. This group was largely responsible for formulating initial program concepts, cultivating wide community support, and advancing the program through a successful Conceptual Design Review. In consultation with its Board of Directors, JOI suspended formal meetings of the advisory structure in April 2007 due to the competitive acquisitions for the Implementing Organization awards. The Board approved an interim steering committee whose membership provided significant overlap with the advisory structure, but avoided individual or institutional conflicts of interest during the procurements. With the IO awards in place, a significant percentage of the former advisory structure is now formally on the project team. The Consortium for Ocean Leadership is consulting with the interim steering committee, NSF, and other program stakeholders to determine how the program's advisory structure going forward will continue to ensure that the OOI facility meets the needs of the research community, provides necessary community advice and guidance to the program implementers, reviews IO decisions on an as-needed basis, and maintains wider communications with the expected user base and related science disciplines.

As with other projects supported with MREFC account funds, the project team anticipates annual reviews coordinated by the NSF's Large Facilities Office and Division of Ocean Sciences. These reviews are a useful forum to examine the project's progress and overall state of health, and to develop corrective actions if needed. The project team will work with NSF and community advisors to develop an overarching operational framework that addresses facility use and governance. This framework will establish how users interact with the facility and how the facility operates behind the scenes, define groups to oversee the facility's governance and operations, and codify the program's key policies, processes, requirements, and documents.

C. Timeline

The $331.1M investment for the OOI currently planned in the NSF MREFC account will be expended over five years starting after funding approval by the National Science Board in the spring of 2008. Figure 10 shows the overall implementation schedule, from July 2008 to July 2013, by large system components in accordance with the overall Work Breakdown Structure for the project.

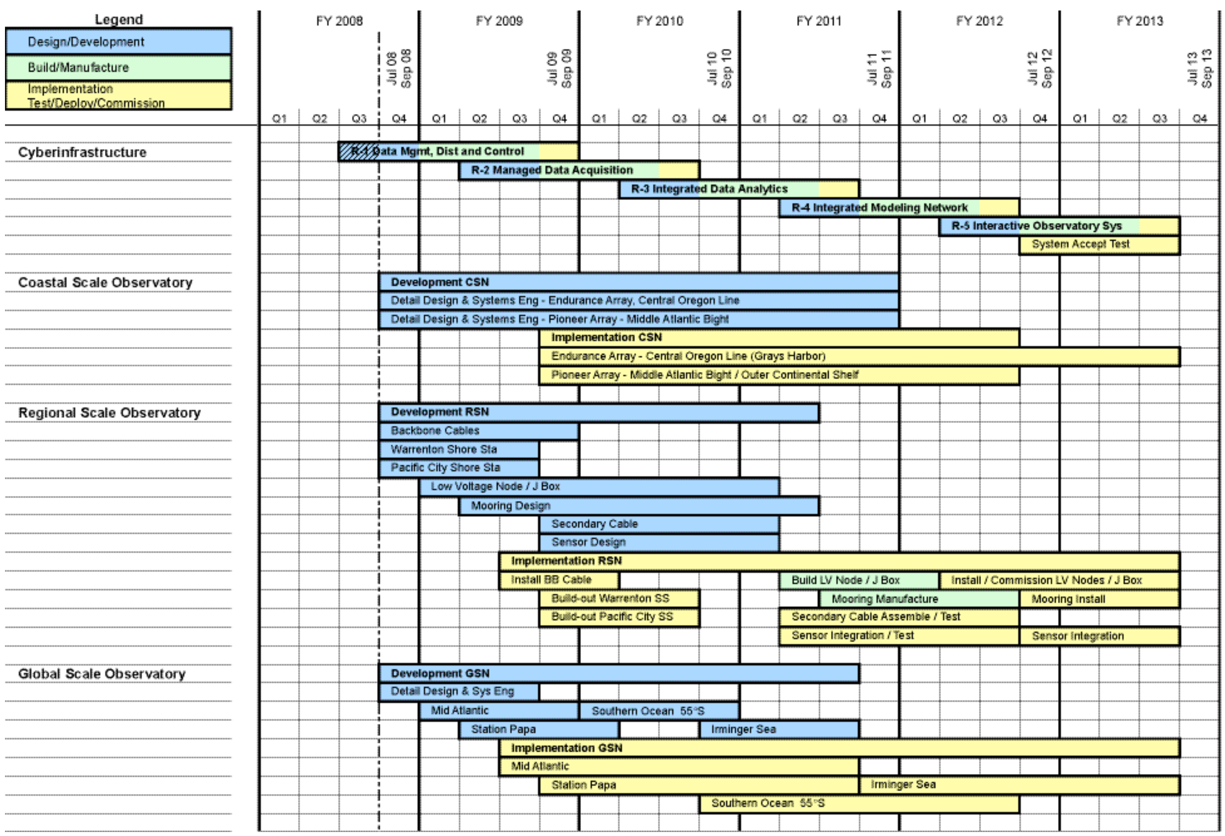


Figure 10. Overall implementation schedule, from July 2008 to July 2013, by large system components in accordance with the overall Work Breakdown Structure for the OOI project.

The first section shows the build cycle for the cyberinfrastructure. Five releases comprise six subsystems that are being developed using a Spiral Development Model. This model relies on close integration with user representatives during the development of each release to ensure that the functionality delivered will be responsive to community needs. The first release will provide rudimentary sensing, acquisition, and data management capabilities and will implement the initial common operating infrastructure. This capability is required to support initial testing of the regional-scale backbone cable and shore stations. The functionality for these subsystems will be enhanced during the development of Releases 2 and 3. The later releases add analysis, synthesis, planning, and prosecution, and will implement the common execution infrastructure. Because the cyberinfrastructure is the key integrating system for OOI, the development of all the required capabilities is essential for the observatory to be fully operational. At present, the critical path for the entire program follows the cyberinfrastructure development path.

The middle section of Figure 10 shows the sequencing of the system's coastal and global components. The initial period will refine requirements and perform system engineering. Due to the high-latitude location of three global nodes, the development time has been expanded and the final construction and installation of the buoys for the Southern Ocean and the Irminger Sea will take place towards the end of the project.

The final part of the timeline shows the development, manufacturing, and integration of the Regional-Scale Nodes. Because the backbone cable purchase and installation is a large bulk cost, its timing must be planned in accordance with NSF's forecasts of annual funding in the Congressional budget. The plan is to purchase this subsystem as early as possible to reduce the potential cost increases if the undersea telecommunications business continues to rebound from its earlier low level of activity. The later part of the timeline depicts the development of the secondary infrastructure and the sensors, followed by an integration and testing period.

The final step in the process is to conduct a system-wide acceptance test. This test will be planned and performed by a coordinated effort of the marine implementing organizations with strong support by the Cyberinfrastructure IO.

D. Budget

The OOI budget has been developed by combining estimates from the IOs into an integrated plan based on the Work Breakdown Structure. Table 1 shows a higher-level summary of the system that reflects the time phasing of the components discussed above. The costs summarized in the table are more accurate than the parametric estimates done during the project's Conceptual Network Design Phase. The new estimates are based on site-specific locations for the major system components and reflect engineering estimates derived from successful OOI proposals and/or similar commercial systems or components. For example, information provided by the IOs was verified from similar components already purchased by NEPTUNE Canada and the MARS testbed.

With MREFC account funding anticipated to start in July 2008, the program begins in the fourth quarter of FY 2008. Table 1 shows that the funding stream is adequate when compared to the time phasing of the individual components planned for implementation. Subaward funding increments will be phased to not exceed available funding.

Table 1. High-level budget summary that reflects the time phasing of OOI components.

	Funding Nominal Total	FY 08	FY 09	FY 10	FY 11	FY 12
Funding Profile	$ 331.11	36.11	80.00	90.00	95.00	30.00

	Nominal (mil) Estimate Total		Contract Year 1 Jul 08 - Jun 09	Contract Year 2 Jul 09 - Jun 10	Contract Year 3 Jul 10 - Jun 11	Contract Year 4 Jul 11 - Jun 12	Contract Year 5 Jul 12 - Jun 13
OOI, Program Roll-Up	***$ 331.11***		***54.15***	***76.35***	***94.57***	***59.01***	***47.02***
NSF Management Reserve (Isern 08/2006)	$ 10.00		-	-	2.00	3.00	5.00
Environmental Impact Reports and Statements	$ 6.20		2.40	0.90	1.60	1.00	0.30
OOI Project Office (including Education)	$ 21.49		4.04	4.17	4.29	4.42	4.56
Cyber-infrastructure	$ 28.79		7.96	7.86	4.72	4.19	4.06
Coastal/Global Scale Observatory	$ 95.50		9.23	17.86	42.57	14.45	11.39
Regional Scale Observatory	$ 169.12		30.52	45.57	39.38	31.95	21.71
Maintenance and Operations							

The estimate includes contingencies based on a risk assessment of the various components of the system. These contingency funds were allocated at the fourth level of the Work Breakdown Structure and are summarized at the higher levels shown. Individual contingencies vary from a few percent for the low-risk areas to as high as 40% for the higher risk tasks, such the high-latitude buoys and the development of the cyberinfrastructure software. Aggregate contingencies are roughly around 20% of each IO's total budget. In addition, NSF has created a program reserve of $10M held at NSF. NSF provided price index numbers from by the Office of Management and Budget to estimate for inflation during the implementation period.

Conclusions

The recent emergence of increasingly complex, interdisciplinary scientific questions, and growing concerns over ever-more challenging societal/environmental problems, provide cogent arguments for developing new approaches to conducting sustained scientific observation in the oceans. The Ocean Observatories Initiative is enabling marine researchers to aggressively pursue innovative techniques for directly observing, quantifying, and interacting with the many dynamically balanced mechanisms and feedback loops operating within the global ocean. These new approaches will be broadly applied, including our first sustained presence in climate-critical, open-ocean environments. The new technologies will allow us to conduct consistent, enduring measurements of key Earth system processes for many years. Delivery of unprecedented power and bandwidth to the water column and seafloor will allow substantial expansion in the number and quality of experiments that can be conducted simultaneously within a defined volume of ocean space. Development and innovative application of sensors for *in situ* chemical and remote biological analysis will combine with adaptive mobile platforms to enable operations of increased autonomy and enhanced energy economy. We can expect the OOI to catalyze shifts in the caliber, the focus, the culture, and the visibility of the Ocean and Earth sciences community devoted to exploring the influence that processes within the ocean basins exert on our quality of life.

The goal of the OOI is to provide a sustained, adaptable infrastructure at selected sites spanning representative processes that are globally significant, expressed locally or regionally, and addressable using new modes of investigation. The assets deployed initially will enable early successes because of the novel infrastructure that uses available sensor suites. During this decades-long program, however, there will be substantial evolution in suites of instruments, footprints of experiments, and interactive sensor technologies. Among the assets of the OOI is the creativity that will emerge from members of the science community as they embrace and apply these new tools. In addition to the suite of opportunities enabled by the infrastructure, advances will come about partly as a result of influences and developments outside the field of oceanography. The use of a large network of space- and time-indexed, interactive assets connected to a global user community via Internet-enabled tools, represents a fundamental shift in oceanic investigative philosophy and capability.

By selecting critical locations at high latitude, where extremes of surface forcing result in major transport of volatiles and heat within and between the ocean and the atmosphere, we are opening new ground for crucially important, long-term studies and longer-range forecasting tied to these instrument-hostile environments. By selecting contrasting east and west coast continental shelf-slope environments, we are enabling immediate treatment of questions spanning the full horizontal and vertical scales of these coastal systems including the impact of climate variability on coastal ecosystems and the role of the coastal ocean in the global carbon and biogeochemical cycles. By focusing at a regional scale, we are including an entire tectonic plate below the divergence of the current between two major oceanic gyres and a productive eastern boundary current. In this regional setting we have a unique opportunity to simultaneously assess major plate tectonic processes and their effects on the overlying ocean, while documenting interannual and decadal forcing of regime shifts that reflect global-scale phenomena.

As the system matures and becomes more extensive and adaptable, users will experience ocean processes as they unfold in real time, using multiple, selectable, *in situ* data streams. Users will follow entire three-dimensional events or phenomena evolving through space and time. Success of the OOI will induce major changes in our scientific interactions, in the complexity of our investigations, and in our style of data assimilation and model development. The technologies will transform our abilities to capture and understand transient and long-term changes. The program will invigorate the public's ability to share in discoveries, insights, and excitement about understanding the ocean.

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Appendix A: Introduction to the Science Traceability Matrix Format

Introduction

Developing the design for the Ocean Observatories Initiative (OOI) Network has been an iterative process of identifying and prioritizing key science questions, the required observations, the technologies needed to support those observations, and in some cases, the environments best suited to making those observations. Science traceability matrices (i.e., graphic representations showing the logical flow from high-level science questions to the OOI infrastructure elements) demonstrate how science questions lead to the design of the proposed OOI infrastructure. In the examples in this appendix, each traceability matrix maps a key science question to the processes to be investigated, to the measurements needed, to the sensors required, to the sampling requirements, and to the system capabilities and infrastructure needed to address the question. The format of the matrices is described below:

Key Science Question Text Box

Sets the context and significance of the question and addresses why the capabilities of the OOI Network are needed to advance (in a transformative way) the research posed by the question. This text box is followed by column headings listed below (progressing left to right in the graphic) to lead the reader from question through processes, observations, sensors, and eventually to the proposed infrastructure.

Science Question – a “subquestion” binned under the overarching Key Science Question.

Processes to be observed.

Spatial Scale of the process to be observed.

Temporal Scale of the process.

Measurements required.

Sensors required to provide the measurements.

Sensors are coded as follows: **Sensors in bold font** have been proposed as core sensors to be installed with the initial OOI capital investment. Other sensors listed are commercially available or in development, but are not designated for purchase as part of the OOI construction at this time. A table of sensors referred to in the matrices is included with their acronyms and/or abbreviations in Appendix B.

Sampling Requirements describes the spatial and temporal frequency of sampling; general description of the capabilities needed to support the required sampling.

Site(s) Required for Science is the justification and/or description of the characteristics of the location that make it amenable to addressing the science question posed.

Experiment Description is high-level description of the infrastructure to support sampling requirements.

The color scheme used in the text boxes is intended highlight the connectivity among the columns and to aid the reader in following the flow of information across the graphic.

TRANSFORMATIVE CAPABILITIES describes the unique aspects and capabilities the OOI Network will bring to the research.

The format used is the result of collaborations of approximately a dozen oceanographers who have been involved in the planning of the Ocean Observatories Initiative Network. These are questions viewed as requiring the proposed observatory infrastructure to make significant and transformative progress. The common thread among these questions is the need for high frequency measurements seasonally, interannually, and, for some questions, over decades. The ten example matrices discussed in the prospectus are as listed below:

List of Science Traceability Matrices

Appendix A-1: Global Biogeochemistry and Carbon Cycling

What are the dominant physical and biological processes that control the exchange of carbon and other dissolved and particulate material (e.g., nutrients, organic matter, dissolved gases, and other materials) across the air-sea interface, through the water column, and to the seafloor?

Appendix A-2: Ocean-Atmosphere Exchange

How important are extremes of surface forcing in the exchange of momentum, heat, water, and gases between the ocean and atmosphere?

Appendix A-3: Ocean Circulation, Mixing, and Ecosystems

How do severe storms and other episodic surface mixing events affect physical, chemical, and biological water column processes?

Appendix A-4: Fluid-Rock Interactions and the Subseafloor Biosphere

How does plate scale deformation mediate fluid flow, chemical and heat fluxes, and microbial productivity?

Appendix A-5: Plate-Scale Seismology and Geodynamics

How do plate-scale tectonic forces translate into local and regional deformation and what is the relation between the localization of deformation and the physical structure of the coupled asthenosphere-lithosphere system?

Appendix A-6: Gas Hydrates

How do tectonic, oceanographic and biologic processes modulate the flux of carbon into and out of submarine gas hydrate formations (i.e., the gas hydrate capacitor)?

Appendix A-7: Climate Variability and Ecosystems

How do climate signals due to forcing at ENSO, NAO, and interdecadal time scales (e.g., PDO) lead to changes in water column structure and chemical and biological properties?

Appendix A-8: Ocean Mixing and Rough Topography

How does topography-driven mixing maintain the observed abyssal stratification?

Appendix A-9: Coastal Ocean Dynamics and Ecosystems - Hypoxia on Continental Shelves

What are the dynamics of hypoxia on continental shelves?

Appendix A-10: Coastal Ocean Dynamics and Ecosystems – Shelf/Slope Exchange Processes

How do shelf/slope exchange processes structure the physics, chemistry, and biology of continental shelves?

Appendix A-1: Global Biogeochemistry and Carbon Cycling

What is the ocean's role in the global carbon cycle?

The ocean modifies, and is affected by, climate; it serves as both reservoir and distributor of heat and carbon dioxide. Understanding the processes of air-sea exchange and sequestration of CO_2 (including anthropogenic CO_2) in the oceans is a critical predicting the effect of CO_2 emissions on climate and ocean ecosystems.

KEY SCIENCE QUESTION

What are the dominant physical, chemical, and biological processes that control the exchange of carbon and other dissolved and particulate material (e.g., gases, nutrients, organic matter) across the air-sea interface, through the water column, and to the seafloor?

The exchange of CO_2 between atmosphere and ocean is mediated by two general mechanisms, the solubility pump and the biological pump. The solubility pump is driven by fluxes and mixing at the air-sea interface, ocean ventilation, and carbonate solubility characteristics. The biological pump is the conversion of dissolved CO_2 into particulate and dissolved organic carbon by marine phytoplankton using light and nutrients. Most of this particulate organic carbon is recycled through complex respiratory paths, however a fraction sinks and is sequestered for long time periods in the deep ocean or buried in marine sediments.

The rates of biological carbon fixation and sequestration are highly variable in the world's oceans. Increasing CO_2 and climate change are projected to have significant impacts on ocean circulation, primary production, biogeochemical cycling, and ecosystem dynamics. Changes to atmospheric forcing, the heat content in the upper ocean, changes in ocean circulation will have regional effects on the exchange of CO_2 across the air-sea boundary. Climate variability influences nutrient distributions, phytoplankton growth, and phytoplankton community composition. Interactions among phytoplankton species and the ocean food web affect the efficiency and amount of carbon exported from the surface waters to the ocean's deep interior and sediments. These interactions could change as increasing ocean CO_2 concentrations decrease ocean pH, which in turn will affect biological calcification rates. Changes to high latitude food webs, especially the North Pacific and Southern Ocean, are possible. Investigating how climate variability will affect ocean circulation, weather patterns, the biochemical environment of the ocean, and marine ecosystems are high priority research topics and compelling drivers for a multidisciplinary ocean observing system.

TRANSFORMATIVE CAPABILITIES

Moored platforms in contrasting regions of the ocean with the capability to provide multidisciplinary, in situ measurements to observe processes and trends of key environmental parameters on daily, seasonal, annual, and decadal scales.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)	Sampling Requirements
What is the spatial (coastal versus open ocean) and temporal variability of the ocean as a source or sink for atmospheric CO_2?	CO_2 flux via the solubility pump and CO_2 flux from atmosphere to ocean via the biological pump. Atmospheric forcing, surface meteorology, wind stress, air-sea exchange of heat, mass, momentum.	*Horizontal*: Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical*: Millimeter to 10s of meters.	*Air-sea interface:* Minutes to days. *Water Column:* Hours to days.	Specific humidity Barometric pressure Wind speed, direction, stress Long, shortwave surface radiation Precipitation Surface wave height Air temperature	**Hygrometer** **Barometer** **Sonic anemometer** **Shortwave radiation pyranometer** **Longwave radiation pyranometer** **Rain gauge** **Motion sensor** **T, P sensors**	*Air-sea interface*: Hourly to daily sampling Surface buoys with the power, data transmission, and physical stability to support (and protect) meteorological instrumentation. Buoys with capability to support subsurface and upper water column profilers with core sensors, with expandability for additional future sensors. The 2-way, near-real time communications to support adjustable sampling intervals to respond to episodic, short-term events or variable-scale phenomena. AUVs and/or gliders to expand/adjust spatial sampling. Time series spanning seasonal, annual, to decadal scales.
	Air-sea exchange/flux of CO_2, O_2.			SST, SSC pCO_2 in air and sea surface (ΔpCO_2) pH DO	**CTD** **IR gas analyzer** **In-water pCO_2 analyzer** **pH** **DO**	
What is the seasonal to interannual variability in particulate (organic carbon) flux?	CO_2 flux via the biological pump: Evolution of the surface mixed layer/near surface ocean.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the surface mixed layer. *Horizontal:* 10s meters to 100s m.	*Water Column:* Hours to days.	Density structure, Horizontal velocity structure (shear), Vertical velocity DO Photosynthetically available radiation Nutrients	**Profiling CTD, Fixed and profiling current meters** **3-axis ADV, ADCP** **DO** **PAR meter** **NO_3**, PO_4, $Si(OH)_4$	Profiling capability to support sampling at: Sub-meter in depths of 1-10 m. Sub-meter to 1-m intervals in mixed layer (to 200 m) 1-m intervals to bottom. Capability to operate in sampling mode over smaller and/or fixed depth intervals. Mixed layer profiles at ~3-hour intervals (note that sampling interval is depth dependent), with capability to adjust sampling frequency to respond to events and/or short-term phenomena. AUVs and/or gliders to expand high resolution spatial sampling. Capability to accommodate future sensors (e.g., gas samplers, nutrient sensors, hyperspectral spectrophotometers etc.).
	Estimated phytoplankton biomass. Estimated gross daily production. Estimated net annual production.	As above	Days to weeks Days to weeks Days to years	Phytoplankton particle mass concentration DO Photosynthetically available radiation.	**Transmissometer** **Chl-a fluor** **DO** **PAR meter** **Others as above.**	
	Bottom boundary layer dynamics. Community respiration.	*Vertical:* 1 to 10s m in near bottom layer, up to 500m above seafloor. *Horizontal:* 10s meters to 100s m.	Minutes to days.	Velocity profile from seafloor to 500m above. Profiles from seafloor to 100m above for: T, S O_2 Particle optical characteristics	**Bottom fixed and profiling current meters :** **ADCP, ADV,** **HPIES (on RSN only)** **Profiling CTD,** **DO** **Fluor, CDOM, bb** **Transmissometer**	
What is the impact of decreasing pH to the chemistry and biology of the ocean?	Changes in distribution of water column properties and constituent concentrations.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the mixed layer. 10s meters to 100s meters for entire water column. *Horizontal:* 10s meters to 100s km.	Days to years.	Density structure, Horizontal velocity structure (shear), Vertical velocity Penetrating solar radiation, Dissolved gases Nutrients, Particulates & bio-optical characteristics.	**Profiling CTD,** **Fixed and profiling current meters (ADCP, ADV)** **Profiling spectral radiometer,** **DO, pCO_2** **NO_3**, PO_4, Fe **Chl-a, CDOM, bb** **Transmissometer**	As above plus: Time series spanning seasonal, annual, to decadal scales. Capability to accommodate future sensors (e.g., gas samplers, multispectral spectrophotometers, nutrient sensors, multifrequency acoustics, optical plankton detectors, etc.).
	Trends in phytoplankton biomass and estimated primary productivity.	Vertical: Sub-meter in upper 10 m to 10s meters throughout the mixed layer. Horizontal: 10s meters to 100s km.	Days to years to decades.	Phytoplankton particle mass concentration DO Photosynthically available radiation.	**Transmissometer** **Chl-a fluor** **DO** **PAR meter**	
	Shifts in phytoplankton community.	As above.	As above.	Size distribution Spectral absorption	**Optical backscatter** Optical plankton Imaging flow cytometer **Multispectral spectrophotometer**	
	Shifts in zooplankton community.	As above.	As above.	Biomass, Size distribution Class identification.	Optical plankton imaging Multi-frequency acoustics echosounder.	
	Shifts in migration patterns of pelagic fish and marine mammals.	*Vertical:* 10s meters throughout upper to mid water column. *Horizontal:*10s meters to 1000s km.	As above.	As above.	Multi-frequency acoustic echosounder Hydrophone.	

Site(s) Required for Science

Global sites ***Station Papa Irminger Sea, and the Southern Ocean/SW Chile*** are sub-polar, open ocean locations considered highly vulnerable to the effects of reduced pH. They are also sites considered representative of ocean regions identified as large sinks for atmospheric CO_2. The ***Irminger Sea and Mid-Atlantic Ridge sites*** are regions with high anthropogenic CO_2 inventories. The ***SW Chile site*** is a geographic region for which little in situ data exists.

The location of ***Station Papa*** in the Gulf of Alaska, the ***RSN*** moorings and the ***PNW Endurance Array*** in the California Current are coupled ecosystems supporting large pelagic fisheries, bird, and marine mammal populations. This region experiences ecosystem regime shifts in response to large-scale atmosphere-ocean interactions (e.g., ENSO, PDO).

The location of the ***RSN nodes*** links basin-scale processes to coastal processes and is also a region that is sensitive to changes in ocean acidity and a CO_2 sink.

Research enabled by the ***Pioneer and Endurance*** arrays will provide for comparative studies of East Coast versus West Coast continental shelves.

The ***Global, RSN, and Coastal moorings*** will provide observations ranging from ocean basin to the coastal ocean, and from temperate to subpolar regions.

Experiment Description

Global sites with stable and capable buoys located in mid to high latitudes will be equipped to supply power and communications to surface and upper water column instrumentation. Sites with sufficient power will support mobile sampling platforms and meteorological and sea-surface sampling instrumentation.

The ***cabled moorings of the RSN*** will provide high power and bandwidth to support water column observations beyond the continental margin. Surface-piercing profiling moorings will monitor water column changes and material transport (e.g., nutrients, dissolved & particulate material). RSN moorings will support benthic sensor packages to augment water column observatories.

The ***PNW Endurance Array*** will be a mixture of cabled and uncabled instrumented moorings with surface buoys to examine air-sea exchange and water column measurements from coastal to open ocean. Surface-piercing profiling moorings will monitor water column changes and material transport (e.g., nutrients, dissolved & particulate material) from nearshore to the continental slope.

The ***Global sites, RSN moorings, and PNW Endurance Array*** will provide for long-term time series for periods up to decades.

The ***Pioneer Array*** will be a mix of closely spaced (10s of km) moorings with surface buoys and subsurface profiling moorings to enable studies of cross-frontal exchange on a broad continental shelf.

Mobile platforms (AUVs and/or gliders) will enable adaptive sampling and allow for extended horizontal observations in the water column at most sites.

Appendix A-2: Ocean-Atmosphere Exchange

KEY SCIENCE QUESTION

How important are extremes of surface forcing in the exchange of momentum, heat, water, and gases between the ocean and the atmosphere?

The lack of observations close to the air-sea boundary during high winds and sea states is a serious impediment to our understanding of air-sea exchange during extreme atmospheric forcing. The availability of these data have been identified as critical to improving the predictive capabilities of storm forecasting and climate change models, and for estimates of energy and material (e.g., carbon) exchange between the upper and deep ocean. Ship expeditions have been largely unable to furnish observations under extreme conditions for reasons of safety. Continuous and simultaneous measurements above and below the air-sea boundary for periods of years to decades would, for the first time, provide the needed measurements of extremes of surface forcing (i.e., from calm conditions to high winds and sea states) over timeframes sufficient to observe episodic, seasonal, annual processes to decadal trends. Moored platforms with sufficient stability, power and communications to support a suite of rugged meteorological and in-water sensors will enable studies of the dynamics marine storms, upper ocean circulation, ocean carbon fluxes, and climate.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)
What is the effect of surface forcing on air-sea fluxes of mass and energy?	Accurate surface meteorology and turbulent flux in high winds & seas (i.e., air-sea exchange of momentum, heat, freshwater).	*Horizontal:* Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical:* Millimeter to 10s meters.	*Air-sea interface:* Minutes to hours.	Air Temperature Specific humidity Barometric Pressure Wind speed and direction, stress Shortwave radiation Longwave radiation SST, SSC Precipitation Surface waves	**Thermistor** **Hygrometer** **Barometer** **Sonic anemometer** **Pyranometer** **Pyrogeometer** **T/C sensor** **Rain gauge** **Accelerometers, rate gyros**
	Turbulent exchange/flux of gases.	As above.	As above.	delta pCO2: pCO2 in air sea surface pCO2 Dissolved oxygen	**IR gas analyzer** **In-water pCO2 analyzer** **DO**
What is the effect on structure of the upper mixed layer?	Dynamics of the surface mixed layer and upper ocean.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the surface mixed layer. *Horizontal:* 10s meters to 100s m.	*Water Column:* Minutes to days.	Density structure, Horizontal velocity (shear), Vertical velocity Dissolved oxygen Penetrating solar radiation	**Profiling CTD, Fixed and profiling current meters** **3-axis ADV, ADCP** **DO analyzer** **Profiling spectral radiometer**
How does variability in surface forcing affect primary productivity (and carbon fixation)?	CO2 flux via the biological pump: Estimated phytoplankton biomass. Estimated gross daily production. Estimated net annual production.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the surface mixed layer. *Horizontal:* 10s meters to 100s m.	Days to weeks. Days to weeks. Days to years.	Phytoplankton particle mass concentration Dissolved oxygen Photosynthetically available radiation	**Transmissometer** **Chl-a fluorometer** **DO analyzer** **PAR Radiometer** **DO**
What are the air-sea fluxes of aerosols and particulates?	Flux of aerosols and mineral dust.	*Horizontal:* Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical:* Millimeter to 10s meters.	*Air-sea interface:* Days to years.	Air-borne particulates Fe, Mn Water vapor	Fe analyzer mass spectrometers Collection of aerosols on filters. Microwave radiometer
Improved estimates of long-term average heat flux over the open ocean.	Baseline global radiation.	*Horizontal:* Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical:* Millimeter to 10s meters.	*Air-sea interface:* Minutes to hours.	Direct and diffuse solar radiation.	Shadow-band radiometers/BSRN sensor.
Improved measurements of turbulence near the air-sea boundary.	Wind stress Lower atmospheric turbulence above the sea surface.	*Horizontal:* Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical:* 10s meter to km.	*Air:* Minutes to hours	Atmospheric wind profiles.	3-D wind profiler.

Sampling Requirements

Air-sea interface:
Hourly to daily sampling
Specialized buoys capable of providing stable platforms in very high winds and sea states. Surface buoys with the power, data transmission, and physical stability to support (and protect) meteorological instrumentation.
The 2-way, near-real time communications are needed to support the capability for adjusting temporal and vertical sampling intervals to respond to episodic, short-term events or variable-scale phenomena.

AUVs and/or gliders to expand/adjust spatial sampling.

Buoys with capability to support subsurface and upper water column profilers with core sensors, with expandability for additional future sensors.

Profiling capability to support sampling at:
Sub-meter at 1-10 m depth,
Sub-meter to 1-m in mixed layer (to 200 m)
1-m intervals to bottom.

Capability to operate in sampling mode over smaller and/or fixed depth intervals.

Mixed layer profiles at ~3-hour intervals (note that sampling interval is depth dependent), with capability to adjust sampling frequency to respond to events and/or short-term phenomena.

AUVs and/or gliders to expand high resolution spatial sampling.

Capability to accommodate future sensors (e.g., gas samplers, and BSRM radiometers, acoustic thermometry, hyperspectral spectrophotometer, etc.).

Site(s) Required for Science

Global sites Station Papa, Irminger Sea, and the Southern Ocean/SW Chile are sub-polar, open ocean locations routinely subjected to high winds and waves. These sites are representative of ocean regions identified as large sinks for atmospheric CO2. The SW Chile site is a remote geographic region for which few continuous, in situ measurements of heat and gas exchange exist.

Contrasting with the other Global sites, the ***Mid-Atlantic*** site is a lower latitude site in a low productivity, high dust region.

The temperate coastal ocean is also subject to a broad range of surface forcing. The ***PNW Endurance Array*** is located on a narrow continental shelf. It will enable observations from the nearshore to continental margin for periods up to decades. The ***Pioneer Array*** will provide observations of greater horizontal resolution on a broad continental shelf.

The ***PNW Endurance Array and Regional Scaled Nodes*** (at nodes equipped with sub-surface moorings) are located in a region where extreme atmospheric forcing regularly occurs. This region supports a rich ecosystem with documented responses to local and remote forcing.

Experiment Description

Global sites Buoys located in mid to high latitude sites equipped to supply power and communications to surface and upper water column instrumentation. Capability to accommodate mobile sampling platforms and support meteorological and sea-surface sampling instrumentation in high sea states.

The ***Irminger Sea, SW Chile, Mid-Atlantic, and Station Papa*** sites will enable studies of air-sea interactions, upper mixed layer processes, deep ocean mixing, and ecosystem processes coupled to climate change in remote and contrasting locations.

Global buoys will be deployed for period of years to decades.

The ***PNW Endurance Array*** will be a mixture of cabled and uncabled instrumented moorings with surface buoys providing a continuous presence to examine atmospheric forcing across a continental margin in extended time series. Sub-surface profiling moorings will monitor water column changes and material transport (e.g., nutrients, particulates, estimated POC) from sea surface to near seafloor. Cabled nodes will support benthic sensor packages to enable observations of deep mixing events.

The ***Regional Scale Nodes (RSN)*** will have the capability to support cabled sub-surface water column moorings with sensor packages comparable to Coastal moorings. When installed, these moorings will provide hydrographic, optical, chemical, and biological data from the continental slope to the deep sea.

The infrastructure of the ***PNW Endurance Array, RSN, and Station Papa*** will enable spatially distributed, time series observations of nearshore coastal ocean to global ocean systems.

The ***Pioneer Array*** will be a mix of closely spaced (10s of km) moorings with surface buoys to examine atmospheric forcing. Subsurface profiling moorings will provide surface to near-bottom observations. The close spacing of these moorings, the high resolution vertical sampling, and the enhanced spatial sampling provided by AUVs and gliders will enable studies of mesoscale processes on a broad continental shelf.

Research enabled by the ***Pioneer and Endurance arrays*** will provide for comparative studies of East Coast versus West Coast, broad versus narrow continental shelves. The ***Global sites and Coastal arrays*** will provide observations ranging from coastal ocean to ocean basins, and temperate to sub-polar regions.

TRANSFORMATIVE CAPABILITIES
The power, bandwidth, and platform stability to enable critically needed observations of extreme atmospheric and physical forcing (high winds, high waves) in remote, open ocean locations in sustained time series.

Appendix A-3: Ocean Circulation, Mixing, and Ecosystems

KEY SCIENCE QUESTION

How do severe storms and other episodic surface mixing events affect physical, chemical, and biological water column processes?

Storm-driven and other episodic mixing events occur everywhere from the nearshore ocean, across continental shelves, and to the open ocean. Turbulent mixing plays an important role in the transfer of energy, heat, and particulate and dissolved materials between atmosphere and the upper ocean. These events also play an important, but as yet, poorly quantified role in the ecosystem dynamics of the ocean. Intense, episodic mixing events may be a greater influence in global air-sea exchange than mean conditions. Episodic mixing events remain difficult to study. The dynamics of turbulent mixing are inherently non-linear, intermittent and so result in complex flow patterns on variable scales. The response of biological systems is also non-linear. The effect of turbulent mixing on nutrient distributions and light availability can result in changes in the productivity and composition of planktonic communities, with cascading impacts to regional marine food webs. It has also been difficult to assess the relative roles of episodic mixing events and the longer term variability in forcing imposed by patterns like ENSO, PDO, or NAO. The high resolution profiles of physical, chemical, and biological parameters over extended timescales are required to advance our understanding of these complex influences and relationships.

TRANSFORMATIVE CAPABILITIES
Sufficient power, bandwidth, and platform stability to support an array of sensors capable of operating under extreme conditions and capable of collecting multi-disciplinary measurements throughout the water column to capture episodic events in the upper ocean.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)	Sampling Requirements
What are the effects of variable strength storms on surface boundary layer structure, nutrient injection in the photic zone, primary productivity, and vertical distribution and size structure of particulate material?	Air-sea exchange of momentum, heat, moisture, and gasses.	*Horizontal:* Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical:* Millimeter to 10s meters.	*Air-sea interface:* Minutes to hours.	Specific humidity Barometric pressure Wind speed and direction Long and shortwave radiation Precipitation Air T, Sea surface temperature, sea surface conductivity pCO2 in air and sea surface Dissolved oxygen	**Hygrometer barometer** **Sonic anemometer** **Solar-IR radiation sensors** **Shortwave radiation pyranometer** **Longwave radiation pyrogeometer** **Rain gauge** **T, P sensors** **CTD** **pCO2 analyzer** **DO** **IR gas analyzer**	*Air-sea interface*: Hourly sampling Storm-driven and other episodic mixing events require specialized buoys capable of providing stable platforms in high winds and sea states. Surface buoys must be able to support (i.e., power, data transmission, physical stability) meteorological (and future gas sampling) instrumentation. Subsurface buoys must be able to support deep and upper water column profilers with core sensors, and have expandability for additional future sensors. The 2-way, near-real time communications are needed to support the capability for adjusting temporal and vertical sampling intervals to respond to episodic, short-term events or small-scale phenomena. AUVs and/or gliders to expand high resolution spatial sampling.
	Mixing layer evolution.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the mixed layer. *Horizontal:* 10s meters to 100s m.	*Water column:* Seconds to hours.	Density structure, Horizontal velocity structure (shear), Vertical velocity, Penetrating solar radiation	**Profiling CTD,** **Fixed and profiling current meters** **3-axis ADV and ADCP** **DO** **Profiling spectral radiometer**	Profiling capability to support sampling at: Sub-meter in depths of 1-10 m. Sub-meter to 1-m intervals in mixed layer (to 200 m) 1-m intervals to bottom. Capability to operate in sampling mode over smaller and/or fixed depth intervals. Mixed layer profiles at frequent (3-6 hr) intervals, with capability to adjust sampling frequency to respond to events and/or short-term phenomena. Profiling and discrete sampling capability as above, especially in upper 200m. AUVs and/or gliders to expand high resolution spatial sampling.
	Redistribution of properties across the base of the mixing layer.	*Vertical:* Sub-meter to 10s meters. *Horizontal:* 10s meters to 100s km.	Seconds to hours.	Density structure, Horizontal velocity structure (shear), Vertical velocity, Penetrating solar radiation, Dissolved gases Nutrients, Particulates & biota.	**Profiling CTD,** **Fixed and profiling current meters (ADCP, ADV)** **Profiling spectral radiometer,** **DO, pCO2** **NO3**, PO4, Si , Fe **Chl-a, CDOM, bb** **transmissometer**	
	Internal wave radiation to interior from surface (and vice versa).	*Vertical:* Meter to 100s meters *Horizontal:* 10s meters to 100s km	Minutes to hours.	Density structure, Horizontal velocity structure (shear)	**Profiling CTD, Fixed and profiling current meters**	
	Benthic boundary layer evolution.	*Vertical:* 10s to 100s meters *Horizontal:* 10s meters to 100s m.	Seconds to hours.	Density structure, Horizontal velocity structure (shear), Vertical velocity, Wave orbital velocity, Particulate concentration.	**Profiling CTD, Fixed and profiling current meters,** **3-axis ADV** **Transmissometer,** **Acoustic backscatter**	
	Changes in the vertical structure of abundance and size distribution of phytoplankton.	*Horizontal:* Variable scales - meters to km *Vertical:* Sub-meter to 10s of meters in the upper 200m.	Days to months.	Biomass, size distribution spectral absorption	**Chl-a fluor,** **Optical backscatter** **Multi-channel spectrophotometer**	
	Particulate resuspension	*Horizontal:* Variable scales - meters to km *Vertical:* Sub-meter to 10s of meters in the upper 200m.	Days to months.	Particle concentration partitioning (organic/inorganic) Dissolved organic matter	**Optical backscatter** **Transmissometer (Beam C)** **CDOM fluor**	Sensors placed within/above benthic boundary layer.
	Dissolved organic leaching	*Horizontal:* Variable scales - meters to km *Vertical:* Meter to 10s of meters.	Days to months.	Dissolved organic matter	**CDOM fluor**	

Site(s) Required for Science

The high latitude ***Global sites (Station Papa, Irminger Sea, and SW Chile)*** are sub-polar, open ocean locations subject to frequent severe storms. These are regions for which time series of atmospheric forcing measurements are rare or in the case of SW Chile, do not exist. All the Global sites are in regions of high energy and CO2 flux and for the Atlantic sites, high anthropogenic CO2 inventory.

The region of the ***PNW Endurance Array*** is subject to physical forcing events on a wide range of spatial (local to basin scale) and temporal scales (days to multiple decades to scales of global change). The location is a prototypical wind-driven upwelling and downwelling system with strong seasonal variations in flow direction. Primary production is influenced by source water characteristics, flow-topography interactions, variability in multiple eastern boundary currents, and the buoyancy input of major rivers.

The ***RSN nodes*** are the deep ocean, end-member for the Endurance Array.

The ***Pioneer Array*** will be located on the broad continental shelf of the Mid-Atlantic Bight. This is an area with high productivity, large horizontal and vertical gradients in water properties, frontal instabilities, and interactions with warm core rings.

Experiment Description

The proposed moorings for the ***PNW Endurance Array***, the ***Global sites***, and subsurface moorings on the ***Regional Scale Nodes (RSN)*** (one or more) will have sufficient power and bandwidth to support sensors required to address the multi-disciplinary aspects of turbulent mixing in ocean ecosystems.

Global sites with physically stable and capable buoys located in mid to high latitude sites will be equipped to supply power and communications to surface, water column, and in some sites, benthic instrumentation. Highly capable sites will support mobile sampling platforms and meteorological and sea-surface sampling instrumentation in high sea states. A capable buoy at ***Station Papa*** would be an important complement to the ***PNW Coastal and RSN mooring(s)***. Capable buoys at the ***Irminger Sea*** and ***SW Chile*** sites would enable studies of air-sea interactions, deep ocean mixing, and ecosystem processes coupled to climate change in remote locations.

The ***PNW Endurance Array*** will be a mixture of cabled and uncabled instrumented moorings with surface buoys providing continuous observations of atmospheric forcing across a continental margin, sub-surface profiling moorings to monitor water column changes and ecosystem response, and material transport (e.g., nutrients, carbon) from nearshore to the continental margins. The cabled ***mooring(s) of the RSN*** will provide water column profiles to the deep ocean, offshore of the Endurance Array.

The ***Pioneer Array*** will be a mix of closely spaced (10s of km) moorings with surface buoys to examine atmospheric forcing and subsurface profiling moorings to enable studies of mesoscale physical processes on a broad continental shelf. Research enabled by the Pioneer and Endurance arrays will allow for comparative studies of the physical dynamics of East Coast and West Coast continental shelves.

Appendix A-4: Fluid-Rock Interactions and the Subseafloor Biosphere

KEY SCIENCE QUESTION

How does plate scale deformation mediate fluid flow, chemical and heat fluxes, and microbial productivity?††

The oceanic crust is the largest fractured aquifer on the planet. Thermally driven fluid circulation through the oceanic lithosphere profoundly influences the physical, chemical, and biological evolution of the crust and oceans. Fluid circulation within this aquifer provides heat and nutrients that sustains a vast microbial biosphere below the seafloor, which is just beginning to be explored. Organisms sampled from high-temperature ecosystems at deep-sea hydrothermal vents have challenged our understanding of the physical and biochemical conditions under which life thrives, survives and expires in the oceanic crust. The nonlinear growth in genomic sciences, concurrent with technological development and processing capabilities make this an area rich in the potential for significant discoveries to be made using the high bandwidth and power capabilities of the RSN. Among the most challenging problems to address in seafloor studies are the spatial scales over which geological, chemical and biological processes are linked and the issue of how these processes vary and co-vary through time.

The major volcanic and tectonic events that create the oceanic crust, modulate the fluxes across the seafloor, and that impact biological communities are inherently episodic on decadal time scales and are also short-lived. Transient events such as magmatic eruptions at mid-ocean ridges increase nutrient (e.g. carbon dioxide) output and venting volume by as much as a factor of 100, resulting in extensive microbial blooms. In margin environments tectonic events release significant quantities of methane gas into the overlying sediments and hydrosphere, which may profoundly perturb microbial communities that thrive on sulfate and methane in these systems. The only way to capture these events and to understand the impact that they have on life on and within the seafloor is to maintain a long-term monitoring capability at a number of sites with high probability for tectonic or magmatic activity. The RSN encompasses two optimal observatory sites to examine these processes:

Axial Seamount is the most magmatically robust volcano on the Juan de Fuca Ridge and hosts several vent fields such that it is a key site to study linkages among seafloor spreading, volcanic activity, and hydrothermal flow. Axial Seamount also hosts a robust subseafloor microbial community and is one of the few sites in the worlds oceans where several year time-series studies have documented temporal changes in microbial communities following an underwater eruption that are linked to changes in fluid chemistry-temperature.

Hydrate Ridge is one of the best studied gas hydrate deposits. Vigorous seeps and formation of gas rich hydrate deposits near the seafloor have been documented through ODP drilling during Legs 146 and 204, and through a series of submersible and ROV dives. The subsurface has been imaged with 3D seismic data, which define a focused plumbing system and provides a clear target for observatory instrumentation.

It is becoming increasingly apparent, however, that the effects of magmatic and tectonic events are not limited to the near field. Stress changes induced by fault motions and the passage of seismic waves from distant earthquakes may trigger earthquakes and perhaps even volcanic eruptions. These punctuated events have been shown to perturb hydrothermal systems and methane seep environments. Hence there is a critical need to link seismometers, flow, and chemical and biological sensors in arrays that range from individual vent or seep sites, to deposits to the plate scale. Seafloor observatories are equally important for understanding the progressive changes in venting systems and the biological communities that occur between major events. These observatories can be used to examine shorter-term perturbations in flow such as those that arise from tides.

One of the most transformational aspects of the cabled system is its ability to provide continuous high power and bandwidth to the seafloor, which allows the transition of shore-based sensors onto the seafloor. Examples include mass spectrometers, flow cytometers, laser raman systems and DNA-on-a-chip analyzers. All of these instruments have been tested/deployed in marine environments and will be invaluable on the cable to evaluate fluid and gas composition of seawater, seeps, and hydrothermal fluids and biological communities in the water column and in vent fluids. Early installation on the cable of core environmental sensors, coupled with in situ temporal sampling, will provide an important foundation for additional development of microbiological sensors, while at the same time provide information on changes in microbial communities through time due to chemical-thermal perturbations.

††Derived from NSF's report *Ocean Sciences at the New Millennium, 2001'* - 'The Ocean Below the Seafloor, Fluid Flow and the Effects of Geology, Chemistry and Life in the Crust'

TRANSFORMATIVE CAPABILITIES

Continuous high power and bandwidth at multiple sites will allow unprecedented, real-time adaptive responses with diverse sensor arrays and sampling to understand the temporal and spatial scales of process linkages and fluxes associated with highly transient events such as earthquakes, faulting and eruptions and the impact of these events on the seafloor biosphere.

Sensors Required: **Bold = Core sensor**

Plate-scale deformation

Science Questions: What are the temporal and spatial scales over which seismic activity impacts crustal hydrology?

Processes: Faulting, melt migration, diking events, pore fluid transients, pore fluid migration, harmonic tremor, aseismic slip, inflation, deflation

Spatial Scale:
- Variable scales – Plate scale, km, to meters
- Intraplate subseafloor to surface

Temporal Requirement: milliseconds to years

Measurements Required:
- Monitor seismicity at plate boundaries, inflation-deflation at spreading centers, subseafloor pressure
- Monitor intraplate seismicity & subseafloor pressure

Sensors Required:
- **Broadband seismometer**
- **Short-period seismometer**
- Strong motion accelerometer
- **Hydrophone**
- **Differential pressure sensor**
- **Current meter**
- **Tiltmeter**
- **SCIMPI**
- Downhole seismometer
- Pressure sensor
- SCIMPI

Site and Sampling Requirements:
- Nodes must be located at all major plate boundaries (subduction zone, transform fault, spreading centers) and at zones of hydrothermal activity and methane seeps. To ensure capturing of events, sites should be located at areas where magmatic, volcanic, and tectonic processes are most active. Sensors now have capabilities for continuous data transmission and are critical for numerous interdisciplinary geological and biogeochemical adaptive response capabilities.
- Nodes must be located distal to plate boundaries, downhole observations required

Experiment Description:

Cabled sensor arrays will span plate boundaries and will be located at:
- Node 1: at the base of the Cascadia Subduction Zone and at Hydrate Ridge – a well studied gas hydrate site and a site with ODP drillholes
- Node 2: Blanco Transform Fault and Blanco Ridge – area has ruptured repeatedly in magnitude 6.1-6.5 earthquakes (5 events since 1967)
- Node 3: Base of Axial Seamount and in summit caldera – most robust, volcanically active portion of the Juan de Fuca Ridge, active seismically. Hosts three active hydro-thermal fields
- Node 4 eastern boundary of the Cascadia Subduction Zone – area of megathrust and slow-slip/tremor events
- Node 5: Mid Plate – ~1/2 way between Node 1 & 3. Allows investigation of strain across an entire plate, and styles and causes of intra-plate earthquakes.

Broadband seismometer at each primary node site will be buried ~ 1 m to dampen background noise and short-period seismometers at Axial Seamount and Hydrate Ridge, and the Subduction Zone will be placed in horizontal boreholes or in seismonuments. Hydrophone will be mounted with seismometers or on moorings. Adjacent current meters with internal temperature sensors and differential pressure sensors will allow filtering of current and tidal processes on seismic signals. To achieve the plate-scale requirement, seismic sensors are augmented by additional seismometers at Neptune Canada sites ODP 889, Barkley Canyon, and ODP Site 1027. Tight arrays of short-period seismometers (< 250 m apart) allow investigation of localized fracturing on fluid and thermal output at Hydrate Ridge and Axial.

Though no current subseafloor observatories exist on the RSN, proposals are underway to develop SCIMPI modual capabilties at Hydrate Ridge at 60-350 mbsf. Subseafloor investigations will be available through NEPTUNE Canada at Site 1027 node on Neptune Canada and ODP 889 at the Cascadia hydrate site off of Vancouver Island

Temperature, chemistry and fluid flow

Science Questions: How does the temperature, chemistry and velocity of hydrothermal flow change temporally and spatially in:
- •subsurface,
- •black smoker,
- •diffuse
- •cold seep &
- •plume environments

How are these systems impacted by tectonic and magmatic events?

Processes: Hydrothermal venting, boiling, metal deposition, condensation, methane hydrate formation & dissolution, gas release, tidal loading, particle settling, along and across circulation, nutrient cycling, mineral-fluid reactions, mineral-biological reactions, plume and megaplume formation

Spatial Scale:
- Base of borehole to surface
- Segment, Vent field, Cluster, Individual vent
- Segment, Vent field, Cluster, Individual vent
- Deposit extent, Individual seep, Vent site
- Segment, Vent field, Seep, 0-300 m above seafloor, 0-1400 m above seafloor

Temporal Requirement: seconds to years

Measurements Required:
- Monitor borehole fluid temperature, composition, velocity, & pressure
- Monitor black smoker temperatures, composition, velocity, & pressure
- Monitor diffuse fluid temperature, composition, velocity, & pressure
- Monitor seep temperature, composition, velocity, & pressure
- Monitor plume thermal anomaly, chemistry, velocity & direction

Sensors Required:
- Thermistor string, Fluid sampler, Mass spectrometer, Pressure sensor, SCIMPI
- **Temperature probes**, **Temperature, resitivity, H_2, H_2S, pH**, **Fluid samplers**, **Mass spectrometer**, Raman Spectrometer, Velocity sensor, **HD video**, **Current meter**, **Low resolution video**, **Digital Still Imagery**, Discrete Samples
- **Temperature probes**, **Fluid Samplers**, **Mass spectrometer**, Raman Spetrometer, **Velocity Sensor**, **Current meter**, **Low resolution video**, **Digital Still Imagery**, Discrete Samples
- **Temperature probes**, **Fluid Samplers**, **Mass spectrometer**, Raman Spectrometer, **Velocity sensor**, **Current meter**, **Low resolution video**, **Digital Still Imagery**, Discrete Samples, SCIMPI
- **CTD-O_2**, **Chemical sensors**, **Transmissometer**, **Current meter**, **ADCP**, AUV docking station, Acoustic scintiallation

Site and Sampling Requirements: Infrastructure must be located at sites of active venting and at active hydrate formation and seepage. Require adaptive data rate collection capabilities to respond to events, capability to retrieve and retain physical samples, ability to retrieve physical samples soon after events occur. High band-width and significant power are required for support of moorings and instrumentation that includes HD cameras, mass and raman spectrometers. These capabilities are also critical for active perturbation experiments that could include heating of clathrates. Subseafloor component would be substantially augmented by future COR, SCIMPI, or small drill-hole installations at active sites.

Experiment Description:

Node 1 hosts prior drill sites and may be instrumented in the future. Site 1027 is an active IODP CORKed observatory and will be connected as part of NEPTUNE Canada

Initial infrastructure includes three tertiary nodes at the ASHES vent field. Site is only one of three in the global ocean where venting has been monitored prior, during, and following a volcanic eruption. Instruments are co-located in vent orifices as stand-alone sensors or in "bundles". HD video will require at least 1.5 Gb/s bandwidth and if stereo 3-6 Gb/s. Mass spec and raman systems will generate 0.5 Gb/s data rates and require up 0.5-1.0 kW ea - providing key chemical and volatile information related to fluid-rock reactions at depth, impacts of magmatic and tectonic events on fluid chemistry. Monitoring of CO_2-H_2 concentrations may allow predictive capabilities on melt migration and eruptions. Temperature-resistivity-hydrogen probes allow examination of boiling and condensation (supercritical phase separation) processes and hydrogen production due to cracking or magmatic injection events. Changes in volatile and acidity of fluids are also monitored through pH-H_2S sensors. Discrete sampling will need to be completed at least annually for calibration of instruments. Fluid samplers will need to be recovered yearly-perhaps autonomously. Two-way communication critical to respond to events and rapidly changing conditions as will be the presence of AUV(s) and docking stations. Vehicles will perform repeat bathymetric and imaging of bottom to monitor growth of structures and morphologic evolution of new/ old vent sites.

Instruments at three tertiary nodes at ASHES are co-located in diffuse sites as stand-alone sensors or in "bundles". HD, digital and low resolution video allow examination of changes in spatial distribution of sites and venting characteristics. Mass spec and raman systems will allow examination of changes in fluid chemistry and impact of biological production/ uptake of nutrients and volatiles. Discrete sampling will need to be completed at least annually for calibration of instruments. Fluid samplers will need to be recovered yearly-perhaps autonomously. Two-way communication critical to respond to events and rapidly changing conditions. Repeat AUV surveys will visually monitor growth/death of diffuse sites

Instruments at two tertiary nodes at Hydrate Ridge are co-located in exposed hydrate and seep sites as stand-alone sensors or in "bundles". Digital and low resolution video allow examination of changes in spatial distribution of sites and seep characteristics. Mass spec and raman systems will allow examination of changes in seep chemistry and impact of biological production/ uptake of nutrients and volatiles. Discrete sampling will need to be completed at least annually for calibration of instruments. Fluid samplers will need to be recovered yearly-perhaps autonomously. Two-way communication critical to respond to events and rapidly changing conditions. Repeat AUV surveys will visually monitor growth/death of seep sites.

Full water column moorings at primary nodes at Hydrate Ridge and Axial may allow investigation of hydrothermal and seep plumes and megaplume chemistry, and thermal and particulate characteristics, respectively, depending on current directions. No moorings are currently planned for the either Hydrate Ridge or Axial at localized seep-vent sites, but extension capabilities at the tertiary nodes will allow installation of local mooring arrays in the future. Moorings for background plumes should be from 0-300 m above the seafloor at Hydrate Ridge, and 0-1300 m above the seafloor at Axial Seamount and located on either end of the caldera. Upward-looking ADCP's on the seafloor and downward-looking ADCP's on moorings will provide information on plume velocity and structure, as will the HD camera at Axial. Repeat nested surveys by AUV's with docking capabilities will allow monitoring of plume chemistry, heat flux, and will provide important event detection response capabilities.

Microbial communities

Science Questions: What is the composition and concentration of microbial material in
- •subsurface
- •vent
- •diffuse
- •sold seep &
- •plume environments

in time and space?

How are these systems impacted by tectonic and magmatic events?

Processes: Biofilm & floc formation, blooms, oxidation/reduction, volatile production and utilization, primary production, mineral-surface reactions

Spatial Scale:
- Base of borehole to surface
- Segment, Vent field, Cluster, Individual vent
- Segment, Vent field, Cluster, Individual vent
- Deposit extent, Individual seep, Individual flow site
- Segment, Vent Field, Deposit

Temporal Requirement: Minutes (response to cracking events, nutrient changes), hours (tidal fluctuations, seismicity), months, years

Measurements Required:
- Monitor community composition & cell # in subseafloor
- Monitor community composition & cell # in black smoker fluids
- Monitor community composition & cell # in diffuse flow
- Monitor community composition & cell # in seeps
- Monitor community composition & cell # in plumes

Sensors Required: Discrete fluid/volatile/rock/ /particulate/hydrate samples*, Time series samples of above (**fluid/microbes**), DNA on a chip analyzers, SCIMPI (seeps), Flow cytometers

**must be coregistered with environmental data in space and time*

Site and Sampling Requirements: Infrastructure must be located at sites of active venting, hydrate formation and seepage. Subseafloor investigations require partitioning of aquifers at depth and sampling of discrete systems at depth. Require adaptive data rate collection capabilities to respond to events, capability to retrieve and retain physical samples, ability to retrieve physical samples soon after events occur. High band-width and significant power are required for support of moorings and instrumentation in the near future that could include in situ flow cytometers, Environmental Process Samplers (DNA on a chip). Such capabilities are also important for perturbation experiments that could include cooling or heating of substrate to monitor impact on biological communities, and injection experiments (tracers, isotopes).

Experiment Description:

Future fluid samplers and DNA analyzers in CORKED and SCIMPI sites will provide lab-based and in situ character-tization of microbes in the subsurface. Time-series fluid-microbial samplers will be part of the NEPTUNE Canada CORKED system at 1027 and surface samplers at ODP Site 889.

Microbial incubators with discrete chambers instrumented with time-series chemical and thermal sensors, and microbial sampling capabilities will require drill holes in chimneys at Axial Seamount. Vent caps will provide examination of microbes in nascent chimneys. Both systems provide time-series sampling/investigation of linked environmental and microbial community structure and evolution through time. Ripe for labeling and perturbation experiments. Samples from particulate DNA samplers (Axial and Hydrate Ridge) will require yearly recovery, perhaps remotely. Two-way communication critical to respond to events and rapidly changing conditions. Discrete sampling of fluids and rock substrate required. Many of critical sensors (DNA on a chip analyzers, in situ flow cytometers await field testing, but should be deployable in 5+ year time frame). Time series fluid-microbial samplers will be part of initial installations at Hydrate Ridge and Axial. Cameras will allow investigation of microbial mat development over time. All sampling and measurements must be tightly coupled to co-located environmental characterization. All sites have extension capabilities to allow follow-on installation of microbiological sensors as they become available.

Appendix A-5: Plate-Scale Seismology and Geodynamics

KEY SCIENCE QUESTION

What are the forces acting on plates and plate boundaries that give rise to local and regional deformation and what is the relation between the localization of deformation and the physical structure of the coupled asthenosphere-lithosphere system?

Tectonic plates are the fundamental building blocks of our planet, with boundaries defined by subduction zones, mid-ocean ridges, and transform faults. The Juan de Fuca plate incorporates a remarkable array of plate tectonic features within a relatively small area, including all major types of oceanic plate boundary and a continent-ocean convergent margin capable of destructive earthquakes. As a consequence, the seismological and geodynamic components of a plate-scale cabled observatory will provide a unique opportunity for long-term monitoring and investigation of the inter-related processes that control the formation, evolution, and destruction of an oceanic plate and of the interactions of that oceanic plate with the leading edge of a continental margin. Understanding the life cycle of an oceanic plate and interactions across the entire plate will require a series of experiments that address processes at a variety of scales, ranging from plate-scale monitoring and imaging (using arrays with apertures of about 1000 km) to more local experiments with apertures on the order of kilometers. This traceability matrix provides the scientific rationale and observing needs of the larger, plate-scale observatory. Because seismic events cause significant perturbations to the hydrology of the oceanic crust, and are indicative of magmatic intrusion and eruptions, real-time data transmission of the RSN is key to realization of these events and optimization of event response capabilities.

At the plate-scale, observations of seismicity and deformation will constrain many important processes including the nature and causes of variations of stress with time across the entire plate, the styles and causes of intra-plate earthquakes, and the coupling of forces across plate boundaries. A plate-scale seismic array will also facilitate studies of the structure and evolution of the lithosphere-asthenosphere system. In combination with data from land-based studies, a plate-scale seismic array will allow unprecedented imaging of the deep and shallow structure that accompanies plate formation, evolution and subduction. Such work would contribute to our understanding of mantle melting, the mechanical coupling of the asthenospheric mantle to the lithosphere, the pattern of return flow from trench to ridge, the nature of mantle flow near contrasting plate boundaries, the rheology of the mantle, and the importance of three-dimensional plate-scale structure for localizing and influencing seismogenic deformation.

This traceability matrix highlights the important scientific benefits of a plate-scale observatory and the observing needs in terms of infrastructure and deployment periods. Because many of the problems of interest require observations at the plate scale, the first priority for a seismic network is to deploy a backbone across the entire Juan de Fuca plate instrumented with broadband seismometers. The plate-scale observatory will provide a regional context for other, more local experiments thus forming an integrated system of multi-scale observatories. The design criteria of a plate-scale observatory are also complementary to many other experiments.

PLATE BOUNDARY

Science Questions: What is the style of deformation along plate boundaries?

Processes: Faulting and fault interaction, melt migration, pressure transients, pore fluid migration, aseismic slip, inflation, deflation, rheological transformations, hydration, dehydration, compression, extension, creep, fault interaction

Spatial Scale Required: Variable scales – Plate scale (ridge, transform, subduction), to meters (vent fields, seeps)

Science Questions: What are the boundary forces on the Juan de Fuca plate and how do the plate boundaries interact?

Spatial Scale Required: Variable scales – Plate scale (ridge, transform, subduction, to km (local arrays)

Temporal Scale: milliseconds to decades

Measurements Required: Monitor seismicity at plate boundaries (including terrestrial component), high quality horizontal- and vertical component long period data (~500 s -50Hz), strong motion, extension, inflation-deflation at spreading centers, tidal pressure, differential pressure, repeat topographic measurements, subseafloor hydrology/pressure transients, anisotropy, velocity and attenuation, background ocean temperature, chemistry and temperature of vents and seeps.

Sensors Required (Bold = Core Sensor):
Broadband seismometer
Short-period seismometer
Strong motion accelerometer
Hydrophone
Pressure sensor
Current meter
Tiltmeter
Acoustic extensometer
Downhole seismometer
Temperature sensors
Vent CO_2, H_2S, H_2,He
Seep CH_2, H_2S, H_2

Site and Sampling Required for Science: Nodes must be located at all major plate boundaries (subduction zone, transform fault, spreading centers) and at zones of hydrothermal activity and methane seeps. To ensure capturing of events, sites should be located at areas where magmatic, volcanic, and tectonic processes are most active. Sensors must have capabilities for continuous data transmission that are critical for numerous interdisciplinary geological and biogeochemical adaptive response capabilities. Optimally would have downhole CORKED observatories for monitoring of pore fluid transients.

Experiment Description: Cabled sensor arrays will span plate boundaries and will be located at:

- Node 1: at the base of the Cascadia Subduction Zone and at Hydrate Ridge – a well studied gas hydrate site and a site with ODP drillholes
- Node 2: Blanco Transform Fault and Blanco Ridge – area has ruptured repeatedly in magnitude 6.1-6.5 earthquakes (5 events since 1967)
- Node 3: Base of Axial Seamount and in summit caldera – most robust, volcanically active portion of the Juan de Fuca Ridge, active seismically. Hosts three active hydrothermal fields and has erupted twice this past decade
- Node 4: eastern boundary of the Cascadia Subduction Zone – area of megathrust and slow-slip/tremor events

A broadband seismometer will be located at each of the primary node sites and will be buried ~ 1 m beneath the sediments to dampen background noise. An additional broadband is located at secondary and tertiary lower voltage nodes at Nodes 3 and 4. At least 8 broadbands, funded by the W.M. Keck Foundation, will be deployed on Blanco Ridge. Short-period seismometers at Axial Seamount (6) and Hydrate Ridge (3) , and the Subduction Zone (3) will be placed in horizontal boreholes or in seismonuments. Hydrophones will be mounted with seismometers and possibly on moorings†. Adjacent current meters, with internal temperature sensors, and differential pressure sensors will allow filtering of current and tidal processes on seismic signals. To achieve the plate-scale requirement, seismic sensors are augmented by additional seismometers at Neptune Canada sites ODP Sites 889, Barkley Canyon, and Endeavour. Tight arrays of short-period seismometers (<250 m apart) allow investigation of localized fracturing on fluid and thermal output at Hydrate Ridge and Axial. Mass spectrometers at venting sites provide chemistry of fluids and delineation on whether near axis seismic events involve melt injection. Coupling of the RSN plate boundary infrastructure with NSF's EarthScope geophysical observatory will significantly extend the capabilities of both of these programs to understand active processes associated with formation and destruction of the Earth's lithosphere.

TRANSFORMATIVE CAPABILITIES

First plate-scale seismic experiment with instruments on all major plate boundaries (spreading center, transform fault, and subduction zone) and intra plate. Seismic and magmatic events dramatically perturb hydrothermal circulation systems that include black smoker and diffuse flow sites, methane seeps and crustal aquifers (see Biosphere traceability). Significant chemical-heat (biological?) fluxes occur during these events, but are routinely missed because of a lack of real-time monitoring and response capabilities. Real-time transmission of seismic data will allow unprecedented response to these events. By monitoring radiated energy over a full seismic spectrum it is also likely that previously unknown signals will be discovered, much in the same way that land-based networks have recently discovered episodic tremor- and slip- phenomena (so called silent earthquakes) along the megathrusts along the Cascadia margin. Deformational events that occur quickly (seismogenic) or slowly ('silent' events) transfer stress to both nearby and distant faults. The plate scale nature of the observatory will allow investigation of stress transfer between the relatively rigid oceanic plate and the advancing margin of a continent that deforms easily and generates destructive earthquakes.

ACROSS PLATE

Science Questions: What are the causes and styles of intraplate deformation?

Processes: Pore fluid migration, diking, seismic and aseismic spreading, crustal strain, lithospheric cooling, tidal loading, sediment loading, compression, extension, hydrothermal flow

Science Questions: What is the return flow from ridge to trench?

Processes: Convection, upwelling, adiabatic decompression, viscosity changes, dehydration, hydration, melting, fractionation, cycling of energy and mass, rheological changes, deformation, dehydration, hydration, earthquakes, slow slip, crustal thickening, magmatism, creep

Spatial Scale Required: Variable scales – Plate scale (ridge, transform, subduction, mid plate) to km (local arrays)

Temporal Scale: milliseconds to decades

Measurements Required: Monitor seismicity at plate boundaries and intraplate (high quality horizontal- and vertical component long period data (~500 s -50Hz), strong motion, extension, inflation-deflation at spreading centers, tidal pressure, subseafloor hydrology/pressure transients, anisotropy, velocity and attenuation, background ocean temperature, chemistry and temperature of vents and seeps

Sensors Required:
Broadband seismometer
Short-period seismometer
Strong motion accelerometer
Hydrophone
Pressure sensor
Current meter
Tiltmeter
Acoustic extensometer
Downhole seismometer
Temperature sensors
Vent CO_2, H_2S, H_2,He
Seep CH_2, H_2S, H_2
SCIMPI's CORKED Observatories

Site and Sampling Required for Science: Nodes must be located at all major plate boundaries (subduction zone, transform fault, spreading centers) at mid-plate sites, and at zones of hydrothermal activity and gas hydrate development. To ensure capturing of events, sites should be located at areas where magmatic, volcanic, and tectonic processes are most active. Sensors must have capabilities for continuous data transmission that are critical for numerous interdisciplinary geological and biogeochemical adaptive response capabilities. CORKED observatories for are required for monitoring of pore fluid transients, but they may also be used for downhole seismometer deployment.

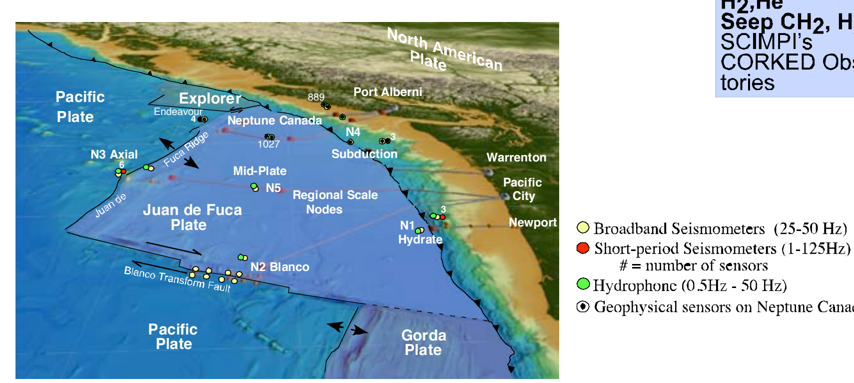
Experiment Description: Experimental lay out is as described as above with the addition of a mid-plate node, Node 5, between Node 1 and Node 3. The node will include a broadband seismometer, hydrophone, differential pressure sensor, and a current meter with an internal temperature sensor. Though no current subseafloor CORKED observatories exist on the RSN, proposals are underway to develop SCIMPI modual capabilities at Hydrate Ridge at 60-350 mbsf. Subseafloor sensors are a cabled component of Site 1027, NEPTUNE Canada.

Science Questions: How much of the oceanic mantle moves with and is coupled to the surface plate

Processes: Viscosity changes, dehydration, hydration, melting, fractionation, thermal-chemical changes, lateral and vertical transport, shearing, volatile exsolution, creep

Science Questions: How and why do stresses vary with time across a plate system?

Processes: Vertical and lateral transport of melt, shearing, spreading, viscosity changes, hydration and dehydration, melt intrusion and eruption, hydrothermal circulation, lithospheric cooling, tidal loading, sediment loading, compression, extension, overpressuring, creep



General location of possible core geophysical sensors on the Regional Cabled Node that would be in place very shortly following installation of the backbone.

†Four hydrophones on 12 m moorings are currently at Axial Caldera (NOAA) and these may also become part of the cabled array.

Appendix A-6: Gas Hydrates

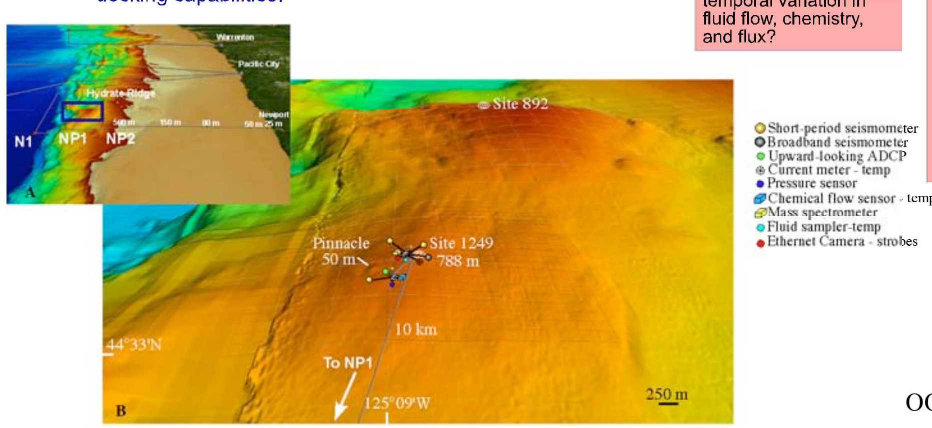
KEY SCIENCE QUESTION

How do tectonic, oceanographic and biologic processes modulate the flux of carbon into and out of the submarine gas hydrate "capacitor," and are there dynamic feedbacks between the gas hydrate methane reservoir and other benthic, oceanic and atmospheric processes?

An over arching goal of establishing observatories where gas hydrates are an important component of the seafloor and subseafloor environment is to understand the role of gas hydrate in modulating the flux of carbon between the solid earth, hydrosphere, biosphere and atmosphere, and to illuminate the role of possible biogeochemical feedbacks in this system. Long-term observations that constrain hypotheses about system evolution and response to transient internal and external forcing are needed to achieve this goal. The planned observatory is an integrated laboratory where nested process studies, including controlled studies of natural and induced perturbations, support our basic understanding and help to better interpret the long term variations.

A significant amount of the methane near the surface of the Earth is locked into gas hydrates in the shallow sediments on continental margins. The hydrates may act as a capacitor in the carbon cycle by slowly storing methane that can be suddenly released into the ocean and atmosphere. Hydrate Ridge (Node 1) in the central Cascadia accretionary complex, is one of the best-studied gas hydrate deposits. Seafloor venting and formation of gas-rich hydrate deposits near the seafloor have been documented at Hydrate Ridge through ODP drilling during Legs 146 and 204 and by a series of seafloor studies using submersibles and ROV's. These studies have provided a basis for understanding how gas hydrate is distributed in marine sediments and the processes that lead to heterogeneity in this distribution. In this area, the subsurface has been imaged with 3D seismic data, which define a focused plumbing system that provides a clear target for observatory instruments to define the temporal evolution of this system, determine material fluxes from the earth into the ocean and understand biogeochemical coupling associated with gas hydrate formation and destruction.

The stratigraphically-controlled plumbing system at Hydrate Ridge contrasts with the gas hydrate system explored on the northern Cascadia margin (Site 889 Stage 1) during ODP Leg 146 and IODP Expedition 311. Here, fluid flow appears to be controlled by structures that cut across stratigraphic horizons. The central and northern Cascadia margins also provide a strong contrast in lithology, with much greater abundance of coarse-grained sediments in the north, which affects the nature of gas hydrate deposition. Establishment of observatories at both sites should, therefore, lead to a comprehensive understanding of gas hydrate processes as a function of lithology, stratigraphy and structure. The real-time, interactive capabilities of the Regional Scale Nodes are critical to studying gas hydrate systems because many of the key processes may occur over short time-scales and will require adaptive response and sampling capabilities (e.g. gas hydrate release due to small and large earthquakes) that include fluid sampling, increases in data accumulation rates on mini-corks (SCIMPI's), seafloor cameras, in situ chemical sensors (e.g., CH_4, H_2S) and repeat high resolution seafloor bathymetric, imaging, and plume surveys by autonomous vehicles with docking capabilities.



A) Star-like topology of the backbone cable for the RSN and possible shore station locations. B) Schematic illustration of infrastructure and possible core sensors at Hydrate Ridge. Also shown are Ocean Drilling Program Sites 892 and 1249.

Science Questions	Processes	Spatial Scale Required	Temporal Scale	Measurements Required	Sensor Required (Bold = Core sensor)	Site and Sampling Required for Science	Experiment Description
What is the role of tectonic, tidal and other forces in driving the flux of carbon into and out of the gas hydrate stability zone out of the sediment? How is this response influenced by geologic parameter (stratigraphy and structure)?	Local, regional and distant earthquake activity, seismic tremors, pressure transients, pore fluid migration (acqueous and free gas), slope failure, hydrate formation and dissolution, bubble formation, compaction, compression, extension, tidal loading, thermal perturbations, lithification, carbonate formation, outflow, inflow, diffusion	Variable scales – plate scale, km, to cm. Subseafloor to seafloor to surface	milliseconds to years	Monitor local, regional and global seismicity ; differential pressure at and beneath the seafloor; ocean current velocity and direction; plume dynamics by imaging and capturing bubbles; gas hydrate and free gas distribution by repeat topographic and subsurface mapping; fluid flow by time series of seafloor and subsurface temperature and with flow meters; CH_4 concentration and phase characterization (gas, dissolved or in gas hydrate) in the formation, discharging fluids at the seafloor and in the water column, using mass spectrometers, raman spectroscopy and other in situ chemical sensors.	**Broadband seismometer** **Short-period seismometer** Strong motion accelerometer **Hydrophone** **Differential pressure sensor** **Current meter** **Flow meters** **Upward-looking ADCP** **Seafloor camera** Downhole pressure, temperature, electrical resisitivity, ground motion (e.g. SCIMPI) Downhole sources (seismic and electromagnetic) for crosshole imaging.	Nodes must be located at all major plate boundaries, mid-plate, and at zones of methane seeps and gas hydrate formation. To ensure capturing of events, sites should be located at areas where hydrate formation and tectonic processes are most active. Downhole observations highly desirable.	Cabled seismic sensor arrays will span plate boundaries as well as mid-plate and include: •Node 1: at the base of the Cascadia Subduction Zone and at Hydrate Ridge – a well studied gas hydrate site and a site with ODP drill holes •Node 2: Blanco Transform Fault and Blanco Ridge – area has ruptured repeatedly in magnitude 6.1-6.5 earthquakes (5 events since 1967) •Node 3: Base of Axial Seamount and in summit caldera – most robust, volcanically active portion of the Juan de Fuca Ridge, active seismically. Hosts three active hydrothermal fields •Node 4 eastern boundary of the Cascadia Subduction Zone – area of megathrust and slow-slip/tremor events •Node 5: Mid Plate – ~1/2 way between Node 1 & 3. Allows investigation of strain across an entire plate, and styles and causes of intra-plate earthquakes. Broadband seismometer at each primary node site will be buried ~ 1 m to dampen background noise and short-period seismometers at Axial Seamount and Hydrate Ridge, and the Subduction Zone will be placed in horizontal boreholes or in seismonuments. Hydrophone will be mounted with seismometers or on moorings. Adjacent current meters with internal temperature sensors and differential pressure sensors will allow filtering of current and tidal processes on seismic signals. To achieve the plate-scale requirement, seismic sensors are augmented by additional seismometers at NEPTUNE Canada sites ODP 889, Barkley Canyon, and ODP Site 1027. Tight arrays of short-period seismometers (located < 250 m apart and sampling rates up to 500 Hz) allow investigation of local seismic activity fracturing on fluid and thermal output at Hydrate Ridge and Axial. Downhole seismometers (sampling rates >500 Hz) record microfractures indicative of fluid flow. Although no current subseafloor observatories exist on the RSN, proposals are underway at IODP to drill at this site and to develop instrumentation for long-term monitoring of sub-seafloor physical properties at depths of 0-350 mbsf (e.g. SCIMPI). Additional subseafloor investigations of contrasting gas hydrate deposits will be available through NEPTUNE Canada at Site 1027 node on NEPTUNE Canada and on the seafloor at ODP Site 889, a gas hydrate site off of Vancouver Island.
What is the significance of pressure change on hydrate stability and methane fluxes due to winter storms and pressure pulses, and bottom currents interacting with topography?	Tidal loading, hydrate formation and dissolution, wave formation, surface and deep water current formation, topographic forcing, bubble formation, fluid flow, plume formation, diffusion		seconds to years	Differential pressure seafloor and subseafloor, current velocity and direction at surface and subsurface, plume dynamics, bubble imaging and capture, repeat topographic mapping and imaging, temperature surface and subseafloor, CH_4 concentration in seeps, bubbles, ocean water, fluid inflow and outflow, discrete fluid and time-series sampling	**Differential pressure sensor** **Current meter** AUV with mapping sonar, chemical sensors, and imaging capabilities Docking station **Time series fluid sampler** **ADCP upward** & down ward-looking **Mass spectrometer** Moorings with profilers and expression at surface **Temperature probes** **Benthic flow meter** SCIMPI **Camera** Velocity meters Bubble imaging system	Sites must be located at areas of gas hydrate formation and seeps. To insure capturing of events, sites should be located at areas where pressure signals may be strong (i.e. areas with intense winter storms) and where there is variable topography. Downhole observations highly desirable and will require partitioning of discrete chemical-fluid zones and sampling of discrete systems at depth.	

TRANSFORMATIVE CAPABILITIES

Continuous high power and bandwidth at multiple sites will allow unprecedented, real-time adaptive responses with diverse sensor arrays and sampling to understand the temporal and spatial scale of process linkages and fluxes associated gas hydrate formation.

Science Questions	Processes	Spatial Scale Required	Temporal Scale	Measurements Required	Sensor Required (Bold = Core sensor)	Site and Sampling Required for Science	Experiment Description
Can natural temperature fluctuations help us understand the effects of long-term temperature change on hydrate stability, or are perturbation experiments required to artificially raise the temperature?	el Nino, la Nina, ocean warming/ cooling, perturbations in offshore currents, upwelling, downwelling, hydrate formation and dissolution, bubble formation, faulting, acidification, stratification, storms	Variable scales – ocean basin, plate scale, km, to cm. Subseafloor to seafloor to surface	minutes to years	Temperature subseafloor, seafloor and throughout water column, current velocity and direction at surface and subsurface, CH_4 concentration in seeps, bubbles, ocean water, fluid inflow and outflow, artificially induced thermal perturbations, discrete fluid and time-series sampling, repeat imaging and sampling of seafloor in time and space	**Temperature probes** SCIMPI's **Mass spectrometer** Seafloor heater **Time-series fluid-gas sampler** **Camera** **ADCP upward** & downward-looking **Current meter** **Benthic flow meter** Discrete fluid-bubble samples	Sites must be located at areas of gas hydrate formation and seeps. To insure capturing of events, sites should be located at areas where there are significant temperature fluctuations due to currents (el Nino, la Nina, Decadal Oscillations), strong upwelling or downwelling. Ability to conduct downhole and shallow heating experiments required.	Initial infrastructure at Hydrate Ridge includes a Primary node at the backbone, The secondary node feeds two low voltage nodes and two medium power junction boxes located at seep sites, 400 m apart. Instruments are co-located in seeps or as stand-alone sensors or in "bundles". Mass spec and raman systems will generate 0.5 Gb/s data rates and require up 0.5-1.0 kW ea - providing key chemical and volatile information related to hydrate-fluid reactions and impacts of tectonic events on fluid chemistry. Three short-period seismometers, and 1 broadband will provide information on seismic activity and a local and regional scale. An upward-looking ADCP will image the plumes and a camera will provide investigation of matt and fauna development and changes through time. Discrete sampling will need to be completed at least annually for calibration of instruments. Fluid samplers will need to be recovered yearly-perhaps autonomously. Two-way communication critical to respond to events and rapidly changing conditions. Repeat AUV surveys will visually monitor growth/death of seeps and changes in topography due to rafting or faulting events. They will also provide valuable information on temporal variation of plume chemistry, intensity, direction. Full water column moorings at primary nodes at Hydrate Ridge and may provide some information regarding methane concentrations in plumes, but additional moorings (at least 2) will need to be installed at Hydrate Ridge proper. Plume investigations and air-sea exchange will be augmented upslope by the presence of the Coastal Nodes Endurance array (5 full water column moorings at 500, 150, 80, 50 and 25 m). Extension capabilities at the tertiary nodes will allow installation of local mooring arrays in the future. Moorings for background plumes should be from 0-300 m above the seafloor at Hydrate Ridge Upward-looking ADCPs on the seafloor and downward-looking ADCPs on moorings will provide information on plume velocity and structure. Repeat nested surveys by AUVs with docking capabilities will allow monitoring of plume chemistry, heat flux, and will provide important event detection response capabilities. Discrete sampling of fluids, hydrate, rock, and sediment required. Many of critical sensors (e.g., DNA on a chip analyzers, in situ flow cytometers await field testing, but should be deployable in 5+ year time frame). Time series fluid-microbial samplers will be part of initial installations at Hydrate Ridge. Cameras will allow investigation of microbial mat development and macrofaunal communities over time. All sampling and measurements must be tightly coupled to co-located environmental characterization. Capabilities exist to allow for future expansion. Future fluid samplers and DNA analyzers in CORKED and SCIMPI sites will provide lab-based and in situ charactertization of microbes in the subsurface. Time-series fluid-microbial samplers will be part of the NEPTUNE Canada CORKED system at 1027. Future AUV's with docking capabilities will allow monitoring of plume chemistry, heat flux, and will provide important event detection response capabilities and nested surveys will allow repeat imaging of the fauna and changes in seafloor topography.
What is the fate of hydrate/seep methane in the ocean and atmosphere? Does significant methane arrive to the atmosphere from hydrate sources?	Hydrate formation and dissolution, acidification, air-sea exchange, upwelling, downwelling, stratification, storms, microbial oxidation, plume formation, tidal loading, topographic forcing, rafting, faulting, seismicity, oxidation, diffusion	Kilometer to micrometer. Seafloor to surface	seconds to years	CH_4 measurements throughout the water column, sea-surface interface, and subseafloor, current velocity and direction at surface and subsurface, imaging of plume dynamics and capturing of bubbles, repeat topographic mapping and imaging, temperature surface and subseafloor, fluid inflow and outflow, artificially induced thermal perturbations, discrete fluid and time-series sampling, C-isotopic analyses	Moorings with profiling capabilities and a surface expression (winch) **ADCP upward** & down ward-looking **Mass spectrometer** **Time-series fluid-gas sampler** Discrete fluid sample Current meters Bubble imaging system	Sites must be located at areas of gas hydrate formation and seeps. Instrumented moorings with profiling capabilities and winches to reach the air-sea interface will be required.	
Are there temporal variations in animal/microbial activity and composition that are affected by temporal variation in fluid flow, chemistry, and flux?	Hydrate formation and dissolution, storms, downwelling and upwelling, bubble formation, hydrothermal flow, faulting, over pressuring, plume formation, microbial oxidation, sulfate reduction, bioturbation, lithification, carbonate formation, compaction, hydrate rafting, symbiosis, community succession	Kilometer to micrometer	seconds to years	Time-series sampling of animals, microbes (subseafloor, surface, carbonate deposits), fluids, sediments, hydrates, and carbonate deposits, CH_4, H_2, H_2S, SO_4, organics etc concentrations in seep fluids, inflow and outflow velocities and volume, culturing, genomic and physiology analyses, C-S-N isotopic analyses, activity experiments, repeat imagery of sites, temperature of fluids, and subsurface.	**Current meter** SCIMPI AUV with mapping sonar, chemical sensors, and imaging capabilities Docking station **Time series fluid sampler** **ADCP upward** & down ward-looking **Mass spectrometer** Moorings with profilers and expression at surface **Temperature probes** **Benthic flow meter** **Camera** Animal and microbe samples Samples of fluids, rocks, sediment In situ DNA analyzers In situ flow cytometers	Infrastructure must be located at sites of active hydrate formation and seepage. Require adaptive data rate collection capabilities to respond to events, capability to retrieve and retain physical samples, ability to retrieve physical samples soon after events occur. Subseafloor investigations require partitioning of aquifers at depth and sampling of discrete systems at depth. High bandwidth and significant power are required for support of moorings and instrumentation that includes cameras, mass and raman spectrometers (and eventually DNA on a chip analyzers, and in situ flow cytometers). Such capabilities are also important for perturbation experiments that could include cooling or heating of substrate to monitor impact on biological communities, and injection experiments (tracers, isotopes). Subseafloor component would be substantially augmented by future COR, SCIMPI, or small drill-hole installations at active sites.	

Appendix A-7: Climate Variability and Ecosystems

KEY SCIENCE QUESTION

How do climate signals due to forcing at ENSO, NAO, and interdecadal time scales (e.g., PDO) lead to changes in water column structure and chemical and biological properties of ocean ecosystems?

The influences of atmospheric forcing at seasonal to inter-decadal scales occur everywhere in the ocean, from the nearshore, across continental shelves, and the deep sea. Understanding when and how marine ecosystems (and food webs) shift from one equilibrium state to another is widely debated and an important area of research with applications to marine resource management. Many ocean food webs appear to be undergoing major regime shifts. Limited time series data in the sub-tropical North Pacific show substantial changes in chlorophyll levels, and zooplankton and pelagic fish biomass during the mid-1970s and late 1980s. Early evidence indicates another shift may have occurred in the late 1990s. The climate of the North Atlantic has also shifted over the last forty years with changes in ocean circulation and declines in copepod and Atlantic cod stocks. Sorting out the causes, processes, and consequences of inter-annual variability, ENSO-scale cycles, and inter-decadal cycles requires high-frequency, sustained time-series data across a spatial range from coastal to global oceans. Understanding the nature of these regime shifts is critical to understanding the consequences to ocean systems and management of living marine resources.

TRANSFORMATIVE CAPABILITIES
Continuous, long-term presence of observing infrastructure with sufficient power and bandwidth to support multidisciplinary arrays of sensors providing the coherent observations needed to study the seasonal to decadal variability in ocean ecosystems.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)	Sampling Requirements
What are the effects of climate signals on variability in water column structure, nutrient injection in the photic zone, primary productivity, and vertical distribution and size structure of particulate material?	Variability in atmospheric conditions, forcing, and air-sea exchange of momentum, heat, moisture, and gases.	*Vertical:* Sub-meter to 10s meters. *Horizontal:* Variable scales - meters to km; tens of km and greater for large scale atmospheric processes.	*Air-sea interface:* Minutes to hours.	Specific humidity Barometric pressure Wind speed and direction Long and shortwave radiation Precipitation Air temperature, Sea surface temperature, sea surface conductivity Dissolved oxygen	**Hygrometer** **barometer** **Sonic anemometer** **Pyranometer** **Pyrogeometer** **Rain gauge** **Thermister** **CTD** **DO**	*Air-sea interface:* Continuous hourly to daily sampling for years to decades. Observations of variability and trends at ENSO to inter-decadal time scales require a continuous, long-term presence of sampling platforms in the coastal and open ocean. Surface buoys capable of supporting a suite of meteorological instrumentation. Sub-surface buoys capable of supporting upper and deep water column profilers. Two-way, near-real time communications enable adjustments to temporal and vertical sampling intervals in response to short-term events or small-scale phenomena. AUVs and/or gliders to expand high resolution spatial sampling and enable adaptive sampling for episodic or short-term phenomena.
	Variability in water column structure and upwelling/ downwelling patterns.	*Vertical:* Sub-meter in upper 10 m to 100s meters throughout the water column. *Horizontal:* 10s meters to 100s m.	*Water column:* Minutes, days, decades.	Density structure, Horizontal velocity structure (shear), Vertical velocity, Penetrating solar radiation	**Profiling CTD,** **Fixed and profiling current meters** **3-axis ADV and ADCP** **DO**	Profiling capability to support sampling at sub-meter to meter intervals in mixed layer (to 200 m); 1-m intervals to bottom. Capability to operate in sampling mode over smaller and/or fixed depth intervals to sample property gradients and/or biological layers.
	Redistribution of properties throughout water column.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the mixed layer. 10s meters to 100s meters for entire water column. *Horizontal:* 10s meters to 100s km.	Minutes, days, decades.	Density structure, Horizontal velocity structure (shear), Vertical velocity, Penetrating solar radiation, Dissolved gases Nutrients, Particulates & bio-optical characteristics.	**Profiling CTD,** **Fixed and profiling current meters (ADCP, ADV)** **Profiling spectral radiometer,** **DO, pCO2** **NO3**, PO4, Si , Fe **Chl-a, CDOM, bb** **transmissometer**	Upper water column profiles at intervals of several profiles per day (depth dependent), with capability to adjust sampling frequency to respond to events and/or short-term phenomena. Deeper water column profiles daily.
	Internal wave radiation	*Vertical:* Meter to 100s meters *Horizontal:* 10s meters to 100s km	Minutes to years.	Density structure, Horizontal velocity structure (shear), barotropic/baroclinic tides.	**Profiling CTD,** **Fixed and profiling current meters (ADCP, ADV)**	
	Changes in the vertical structure of abundance and size distribution of phytoplankton.	*Vertical:* Sub-meter to 10s of meters in the upper 200m. *Horizontal:* Meters to 100s km.	Days to months; years to decades.	Biomass, size distribution spectral absorption	**Chl-a fluor**, **Optical backscatter** **Multi-channel spectrophotometer**	
	Particulate transport.	*Vertical:* Sub-meter to 10s of meters in the upper 200m. *Horizontal:* Meters to 100s km.	Days to years.	particle concentration partitioning (organic/inorganic) Dissolved oxygen matter	**Optical backscatter** **Transmissometer (Beam C)** **CDOM fluor**	
	Changes in, zooplankton, fish, larvae, and other nekton abundance.	*Vertical:* Meter to 10s of meters in the upper 200m. Meter to 10s meters in deeper depths. *Horizontal:* Meters to 100s km.	Days to months; years to decades.	Biomass, size distribution class identification.	Plankton optical imaging sensors, Multi-frequency acoustics, **Hydrophones**.	Sufficient power and bandwidth to support additional and advanced sensors.

Site(s) Required for Science

The ***PNW Endurance Array*** is located in a highly energetic and productive ecosystem. It supports high standing stocks of phytoplankton, zooplankton, shell- and finfish, birds, and mammals. This region is subject to physical forcing events on a wide range of spatial (meters to basin scale) and temporal scales (days to multiple decades to scales of global change). The PNW coastal ocean is a prototypical wind-driven upwelling and downwelling system with strong seasonal variations in flow direction and primary production. Primary production is influenced by source water characteristics, flow-topography interactions, variability in multiple eastern boundary currents, and the buoyancy input of major rivers.

This region is sensitive to inter-annual and decadal atmosphere-ocean interactions (e.g., ENSO, PDO).

Global site ***Station Papa*** represents the "upstream" end of the start of the California Current System off Washington and Oregon. This site is in a region of relatively high global productivity and net CO2 uptake.

Cabled, sub-surface water column moorings on the ***Regional Scale Nodes (RSN)*** could provide important regional continuity linking ***Station Papa*** and the ***Endurance Array***.

The ***Irminger Sea*** Global site is in a productive ecosystem with fisheries that are tightly coupled to climate variations such as the NAO. This is also a region of high CO2 uptake linked with water mass formation. The ***Mid-Atlantic site*** at lower latitude and located in the less productive subtropical gyre is a contrasting site to Irminger in examining changes in NAO indices.

The ***SW Chile site*** is a region for which little data (no time series data) exists to document system responses to climate variability.

The ***Mid-Atlantic Pioneer Array*** will be located on a broad shelf with high productivity, and large horizontal and vertical gradients in water properties and velocities. This is a region influenced by periodic phase changes in the NAO index. Although this infrastructure is to be deployed for five years, it will provide a high spatial and temporal resolution time series for that period.

Experiment Description

The ***PNW Endurance Array*** will be a mixture of cabled and uncabled instrumented moorings with surface buoys providing a continuous presence to examine atmospheric forcing across a continental margin, sub-surface profiling moorings to monitor water column changes in ecosystem response, and material transport (e.g., nutrients, carbon) from nearshore to the continental margins. Cabled moorings will be capable of supporting benthic sensors, and will enable future additions of advance sensors (e.g., nutrient sensors, optical plankton detectors, genomic sensors, etc.).

The ***Regional Scale Nodes (RSN)*** will be capable of supporting cabled sub-surface water column moorings to support sampling at the boundary of the continental slope to the deep ocean. These moorings will also have the high power and bandwidth to accommodate future sensor additions.

Global site buoys located in mid to high latitude sites equipped to supply power and communications to meteorological, sea surface, water column, and in some sites, benthic instrumentation. Highly capable sites will support mobile sampling platforms and meteorological and sea-surface sampling instrumentation. These sites will enable studies of changes/trends in atmospheric forcing,
deep ocean mixing, and ecosystem processes coupled to climate change in remote locations.

The integration of data from ***Global site Station Papa, RSN mooring(s), and the Endurance Array*** will provide a high resolution time series for ecosystem variability in the Northeast Pacific.

The ***Pioneer Array*** will be a mix of closely spaced (10s of km) moorings with surface buoys to examine atmospheric forcing and sub-surface profiling moorings to enable studies of mesoscale physical processes and phytoplankton abundance.

Research enabled by the ***Pioneer and Endurance Arrays*** will provide for comparative studies of climatic variability on East and West Coast continental shelves.

The combined ***Global sites, Coastal Arrays, and RSN mooring(s)*** will enable comparative studies of climate variability and system response in two oceans.

Appendix A-8: Ocean Mixing and Rough Topography

KEY SCIENCE QUESTION

How does topography-driven mixing maintain the observed abyssal stratification?

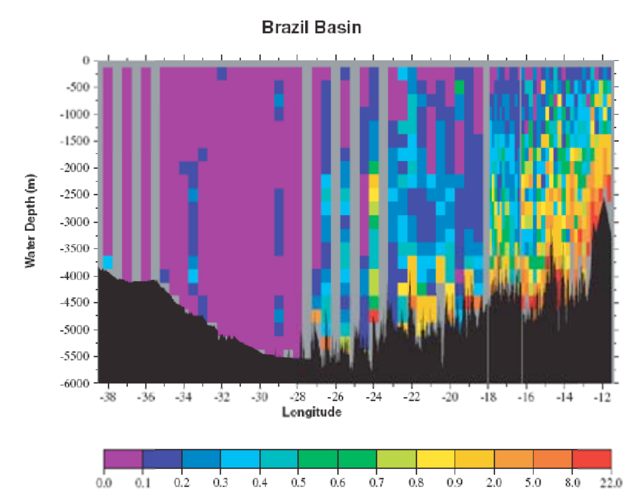
Measurements to date imply that there is insufficient turbulence in the deep interior oceans away from the boundaries to produce enough vertical mixing to account for the vertical profile of temperature. In short, the deep ocean is warmer than it should be given observed levels of in situ turbulence that can mix surface heat downward. Surface heat in the tropics and sub-tropics has to be mixed downward to balance the upwelling of the cold bottom waters formed at high latitudes that disperse into all ocean basins. Without some mechanism of downward mixing of heat, in about 3000 years the entire ocean beneath the thermocline would fill up with the very cold water created at high latitudes. Formation of such a deep, thick isothermal layer would have serious physical, biological and climatic implications, including the cessation of the very convection of cold water that created it, thus halting the pull of warmer sub-tropical water toward the poles, especially in the far North Atlantic. This Meridional Overturning Circulation (MOC), considered an important contributor to the relatively warm climate of Europe, would cease to exist. This, at least, is one highly regarded hypothesis of the importance of the abyssal stratification. Understanding how the abyssal stratification is maintained is a critical issue for understanding potential variations in the MOC and resultant climatic impacts.

Observations in the past 15 years have uncovered enhanced levels of turbulence near the water-earth boundary in regions of rough and and/or acute topography. The proposition, now well established, is that the required vertical mixing to maintain the abyssal stratification occurs near regions of strong topography, with the mixed products being distributed horizontally by mesoscale eddies and "mean" currents. Many physical mechanisms have been identified as possible contributors to the topography-catalyzed mixing. Sorting out the nature of these mechanisms, their relative importance, their temporal and spatial variability, their dependence on changes in environmental factors (e.g., mesoscale current strength, internal wave energy levels), and how they can be parameterized in models of the ocean's general circulation and climate, are among the many issues that need urgent attention and which require rapid sampling of physical variables (vertical turbulent overturning is, after all, a fast process) over long periods of time. Such an observational regimen is only possible with sustained observation platforms that provide continuous and plentiful power, as well as high bandwidth data communications, such as provided by the OOI's Regional Scale Nodes.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)	Sampling Requirements	Site(s) Required for Science	Experiment Description
What processes are responsible for the enhanced near-boundary mixing? What are the spatial and temporal variability, and steady state dynamics of these processes? How are these processes engendered and/or modulated by the general circulation, mesoscale eddies, mesoscale waves, inertial wave energy levels, barotropic tides, baroclinic tides, higher frequency internal wave energy levels, and ambient stratification?	Stress-driven boundary layer mixing by the following: barotropic tides; ridge-trapped waves; energetic mesoscale eddies; and constriction and acceleration of sub-inertial barotropic currents through ridge channels. Enhancement of shear and strain leading to instabilities outside (as well as within) the bottom boundary layer by the following: barotropic tide forcing of internal tides; lee wave generation by sub-inertial motions, including infrequent mesoscale eddies, barotropic motions, and ridge-trapped waves; and non-tidal internal wave reflection at the critical frequency/slope.	*Vertical:* Microstructure and turbulence has scales of centimeters to meters. Shear and stratification related to internal waves at depth have 1-100m scales. Scales also set by "local" bottom roughness (sub-meter to meters), thickness of boundary layer ~100 - 200 m, and height of topography. *Horizontal:* Depends on the scale of the topography.	Microstructure and boundary layer turbulence on the order of 1 - 100 seconds. Internal waves with period ~10 minutes in the main thermocline, while overturning at depth has time scales of over 2 hours. Tides likely set the primarily scale - 12 hours.	C, T, P Current velocity. Particle mass.	**Profiling CTD** **Acoustic current meter** **Optical backscatter (to detect prior interaction with the bottom)**	Profiling from near surface to bottom at 1-m intervals with adaptive sampling capability; 4 vertical samples/temporal scale.	The Regional Scaled Nodes are representative of a variety of topographies: The Endurance Array and Node 1 are in the shelf break and slope; Node 2 is located at a fracture zone; Node 3 is proximal to seamount and ridge; Node 4 is the base of slope; and Node 5 is flat plain. It will be possible to generalize the results obtained here to the topography of the global ocean.	RSN primary sites and some of the Coastal Endurance sites will support profiling mooring systems, basic bottom sensor suites, and mobile platforms. These sites will provide continuous, long-term data streams. Long-term and continuous measurements supported by the RSN and Endurance Array are essential to obtain statistical power in the results, and to adequately sample the highly intermittent events that are the ubiquitous signature of mixing. The RSN is an ideal laboratory to study the connections between the solid earth and the water column - here in relatively simple physical terms, but eventually applying this to understanding material fluxes across the seafloor interface.
				Dissipation and fluxes from: Shear and stratification using Thorpe-scale and Gregg-Henyey parameterization Large scale barotropic and 1st baroclinic flow.	**HPIES (horizontal electric field for depth averaged velocity, pressure, inverted echo-sounder).**	The HPIES will characterize the gravest modes of the ocean variability (e.g., the large-scale forcing - eddies and "mean" currents").		
				Horizontal dependence of stratification	**Glider with CTD, optical backscatter**	Glider to expand the basic footprint, acting as a virtual mooring to sample the variability on the scale of the topography variations.		
				Bottom boundary layer turbulent velocity, density, and stress.	**Bottom-mounted ADCP (through boundary layer, nominally 200 m, 150 kHz)** Temperature/conductivity chain, 0-200 m, variable spacing < 10 m)	Bottom boundary layer measurements using the ADCP and the T/C chain will have a 1-s sample rate.		
				Dissipation and fluxes from: Dissipation rates for energy and scalars	Microstructure/ dissipation sensors	Microstructure sensors will be deployed on profilers for nominally 1 year to validate Thorpe and Gregg-Henyey calculations based on profiling CTD and velocity data, before being moved to next site.		

TRANSFORMATIVE CAPABILITIES

Only with the power and bandwidth of the cabled RSN and Endurance Array moorings can the adaptive, long-term measurements required be made. Profiler technology with sufficient power to sample continuously through the water column, with the real-time capability of adapting its sampling in response to highly intermittent mixing events (e.g., an overturning and breaking internal wave, or a lee wave coming off a ridge).



Turbulent diapycnal eddy diffusivity K in the Brazil Basin shows weak mixing (less than 0.1 x 10^{-5} $m^2 s^{-1}$) over the smooth topography to the west and bottom-elevated mixing (K> 10x10^{-5} $m^2 s^{-1}$) over the rougher topography of the Mid-Atlantic Ridge to the east (adapted from Mauritzen et al. 2002). Kunze, E. and Llewellyn Smith, S.G. (2004). Oceanography Vol. 17(1): 55-64.

Appendix A-9: Coastal Ocean Dynamics and Ecosystems - Hypoxia on Continental Shelves

KEY SCIENCE QUESTION

What are the dynamics of hypoxia on continental shelves?

Unlike hypoxic events fueled by anthropogenic nutrients and/or limited circulation of semi-enclosed estuaries or embayments, hypoxia on continental shelves is driven by atmospheric forcing, upwelling/downwelling, and variability in ocean circulation. Low dissolved oxygen concentrations have been documented in the coastal ocean waters of the Pacific Northwest during late spring to summer of 2002 to 2007. Upwelling brings nutrient-rich, oxygen poor waters onto the shelf fueling phytoplankton blooms which, in turn, reduce oxygen levels in the near-seafloor water column through decomposition and respiration. The alternating periods of upwelling and downwelling generally sets the stage for intensity and duration of shelf hypoxic events. Surveys have shown these are large-scale events (on the order of 3000 km2) and have serious impacts to the coastal ecosystem, including mass die-offs of commercially important shellfish and finfish. In contrast, the 2002 event was triggered by an invasion of low oxygen, subarctic water from the Gulf of Alaska. This "anomalous" source water was advected onto the Pacific Northwest shelf depressing dissolved oxygen levels in offshore waters from Vancouver Island to southern Oregon. The formation, duration, and extent of hypoxic areas are subject to climate variability and variations in oceanic flow on seasonal, inter-annual, ENSO, and inter-decadal scales. Understanding hypoxic events and impacts to PNW marine ecosystems requires the ability to observe physical, chemical, and biological conditions across the continental shelf to slope waters, for periods spanning weeks to years (seasonal to inter-annual change) to decades (ENSO and PDO shifts). The Endurance Array will support multi-disciplinary suites of sensors to provide continuous observations of atmospheric forcing, ocean circulation, and biological, chemical, and physical processes from sea surface to near sea floor. The infrastructure of this array (including high powered cabled moorings, uncabled moorings surface moorings, and gliders) will support studies to understand the interaction among upwelling/downwelling cycles, primary productivity, oceanic flow, sub-Arctic intrusion, and the longer-term trends imposed by climate variability as causes shelf hypoxia. Observations from the deeper, off-shore moorings can also serve as early warning of low oxygen intrusions in support of both research opportunities and resource management strategies.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)	Sampling Requirements
What are the relative contributions of low-oxygen, nutrient rich source water, phytoplankton production from local upwelling events and along-shore advection, and local respiration in driving shelf water hypoxia in the northern California Current?	Variability in atmospheric conditions, forcing, and air-sea exchange of momentum, heat, moisture, and gases.	*Vertical:* Sub-meter to 10s meters. *Horizontal:* Variable scales - meters to km; tens of km and greater for large scale atmospheric processes.	*Air-sea interface:* Minutes to hours. *Water Column:* Minutes to days.	Specific humidity Barometric pressure Wind speed, direction Shortwave radiation Longwave radiation Precipitation Air temperature Sea surface temp Sea surface cond Dissolved oxygen	**Hygrometer** **Barometer** **Sonic anemometer** **Pyranometer** **Pyrogeometer** **Rain gauge** **Thermister** **CTD** **DO sensor**	*Air-sea interface:* Continuous hourly to daily sampling for years to decades. Surface buoys capable of supporting a suite of meteorological instrumentation to observe changes in heat flux, gas and material flux, incident radiation. *Upper water column:* Surface buoys with near surface sensors for T, C, and DO and/or sub-surface buoys capable of supporting upper water column profilers with multi-disciplinary sensor arrays.
	Variability in water column structure and upwelling/downwelling patterns.	*Vertical:* Sub-meter in upper 10 m to 100s meters throughout the water column. *Horizontal:* 10s meters to 100s km.	*Water Column:* Minutes, days, months, decades.	Density structure Horizontal velocity structure (shear), vertical velocity, barotropic/baroclinic tides.	Profiling CTD Fixed and profiling current meters: (ADCP, 3-axis ADV)	Profiling capability to support sampling at sub-meter to meter intervals in mixed layer (to 200 m); 1-m intervals to bottom. Upper water column profiles at intervals of several profiles per day (depth dependent), with capability to adjust sampling frequency to respond to events and/or short-term phenomena. Deeper water column profiles daily. Sub-surface buoys capable of supporting fixed sensors, and upper and deep water column profilers with multi-disciplinary sensor arrays. Capability to operate in sampling mode over smaller and/or fixed depth intervals to sample property gradients and/or biological layers. Two-way, near-real time communications to enable adjustments to temporal and vertical sampling intervals in response to short-term events or small-scale phenomena. Gliders to expand high resolution spatial sampling and to enable adaptive sampling for episodic or short-term phenomena. Observations of variability and trends at ENSO or NAO to inter-decadal time scales require a continuous, long-term presence of sampling platforms in the coastal and open ocean. Sufficient power and bandwidth to support additional and advanced sensors.
	Distribution of dissolved oxygen and other properties throughout water column.	*Vertical:* Sub-meter in upper 10 m to 10s meters throughout the mixed layer. 10s meters to 100s meters for entire water column. *Horizontal:* 10s meters to 100s km.	Minutes, days, months, decades.	Density structure Horizontal velocity structure (shear), vertical velocity Photosynthetically available radiation Penetrating solar radiation Dissolved oxygen, pCO2, pH Nutrients Chl-a, dissolved organic matter Particulates & bio-optical characteristics.	**Profiling CTD** **Fixed and profiling current meters: (ADCP, 3-axis ADV)** **PAR meter** **Multi-wavelength spectral radiometer,** **DO sensor** **pCO2, pH sensor** **NO3,** PO4, Si(OH)4 , Fe **Chl-a & CDOM fluorescence** **Optical backscatter, transmissometer**	
	Vertical abundance and size distribution of phytoplankton, primary production, and other particulate organic material: Estimated phytoplankton biomass. Estimated gross daily production. Estimated net annual production. Particle size distribution, concentration.	*Vertical:* Sub-meter to 10s of meters in the upper 200m. *Horizontal:* Meters to 100s m.	Days to weeks. Days to weeks. Days to years. Days to weeks.	Phytoplankton particle mass concentration Dissolved oxygen Photosynthetically available radiation. Dissolved oxygen Size distribution, spectral absorption, particle concentration partitioning (organic/inorganic) Colored dissolved organic matter (CDOM)	**Transmissometer** **Chl-a fluor** **DO sensor** **PAR meter** **As above.** **Chl-a fluor** **Optical backscatter** **Transmissometer** **Multi-channel spectrophotometer** **CDOM fluor**	
	Bottom boundary layer dynamics. Community respiration.	Vertical: 1 to 10s m in near bottom layer, up to 500m above seafloor. Horizontal: 10s meters to 100s m.	Minutes to days. Days to months.	Velocity profile from seafloor to surface. Profiles from seafloor to 100m above for: Temp, salinity Dissolved oxygen Particle optical characteristics	**Bottom fixed and profiling current meters : ADCP, 3-axis ADV,** **Profiling CTD,** **DO sensor** **Chl-a & CDOM fluorescence** **Optical backscatter,** **Transmissometer**	
What are the impacts of shelf hypoxic conditions on living marine resources.	Changes to/impact on zooplankton, fish, larvae, and other nekton abundance and migration routes.	*Vertical:* Meter to 10s of meters in the upper 200m. Meter to 10s meters in deeper depths. *Horizontal:* Meters to 100s km.	Days to months; Years to decades.	As above plus: Biomass, size distribution class identification	As above plus: Plankton optical imaging sensors Multi-frequency acoustics **Hydrophones**	As above.
How are wind-driven upwelling, circulation, and biological responses in the coastal zone affected by ENSO, water mass intrusions, and inter-decadal variability?	As above	As above	Days to decades.	As above.	As above.	As above.

Site(s) Required for Science

The **PNW Endurance Array** is located in a highly energetic and productive ecosystem. It supports high standing stocks of phytoplankton, zooplankton, shell- and finfish, birds, and mammals. This region is subject to physical forcing events on a wide range of spatial (meters to basin scale) and temporal scales (days to multiple decades to scales of global change). The PNW coastal ocean is a prototypical wind-driven upwelling and downwelling system with strong seasonal variations in flow direction and primary production. Primary production is influenced by source water characteristics, flow-topography interactions, variability in multiple eastern boundary currents, and the buoyancy input of major rivers.

Near bottom hypoxia has occurred on the PNW continental shelf during the spring/summer from 2002 to 2007. In some cases severe enough to cause mass die-offs of shell and finfish. This region is also sensitive to inter-annual and decadal atmospheric-ocean interactions (e.g., ENSO, PDO).

The **Oregon Line** is located at a well-established site of upwelling. The "upstream" moorings of the **Washington Line** a in a highly productive area with contrasting river influence and bathymetric effects. These two lines will provide the along-shelf component of observations.

Global site Station Papa represents the northern end of the California Current System. The sub-Artic intrusion of 2002 was also detected here.

The sub-surface water column moorings on the **Regional Scale Nodes (RSN)** could provide important regional continuity linking Station Papa and the Endurance Array.

Experiment Description

The **PNW Endurance Array** will be a mixture of cabled and uncabled moorings to support instrumented profilers, benthic instrument packages, and surface buoys. The Newport Line off Oregon will be a cross-shelf series of moorings equipped with profilers to support full water column sampling and positioned to span the nearshore to the continental slope. Two moorings will have surface buoys to support meteorological sensors; all but the nearshore mooring will support benthic instrument packages. The Grays Harbor Line off Washington will be two uncabled moorings, one with an instrumented buoy at mid-shelf; the other a sub-surface profiling mooring on the inner shelf. The two lines provide for along-shelf sampling. Sampling between and beyond the mooring lines will be accomplished with instrumented gliders.

The combined assets will enable examination of atmospheric forcing, variability in currents, dissolved oxygen, nitrate, particulates, and phytoplankton biomass on the continental margin.

Cabled moorings will enable near-real time communications and data access, and be able to accommodate future additions of advance sensors (e.g., other nutrient sensors, optical plankton detectors, genomic sensors, etc.) to better observe ecosystem response.

The **Regional Scale Node (RSN)** cabled mooring at **Hydrate Ridge** will support a sub-surface water column mooring for sampling as the deep ocean end member of the Newport Line. These moorings will be equipped with deep ocean and upper ocean profilers, and have the power and bandwidth to accommodate future sensor additions.

Global site Station Papa will provide comprehensive surface to seafloor observations with paired surface and sub-surface moorings supporting meteorological and benthic sensors. The integration of data from **Station Papa, the Hydrate Ridge mooring, and the Endurance Array** will provide a high resolution time series for ecosystem variability in the Northeast Pacific.

TRANSFORMATIVE CAPABILITIES

The continuous, long-term operation of an instrumented array with the power and bandwidth to support multi-disciplinary sensors providing the observations to study coastal ocean processes from event-scale to inter-annual variability to inter-decadal trends. The PNW Array will enable high resolution observations of cross-shelf gradients in physical and biogeochemical properties from nearshore to the continental slope. Simultaneous observations of the meteorological forcing, oceanic flows, and a range of physical and biogeochemical properties with high vertical resolution will yield an unprecedented view of the coastal ocean ecosystem.

Appendix A-10: Coastal Ocean Dynamics and Ecosystems - Shelf/Slope Exchange Processes

KEY SCIENCE QUESTION

How do shelf/slope exchange processes structure the physics, chemistry, and biology of continental shelves?

Shelf/slope exchange processes are known to be significant conduits of heat, salt and organic matter between continental shelves and the deep sea. These exchange processes are highly variable in space and time; many operate over kilometer scales horizontally and can often be features that are only several vertical meters in size. These processes can last only a few days however, it is believed that extreme events, such as storms, play a disproportionately large role in their maintenance and dissipation. Traditional ship board sampling cannot provide sufficient spatial and temporal resolution to quantify these process; as a result it is not possible to derive robust budgets in carbon, heat, salt, and other properties for continental shelves.

A well defined shelfbreak front extends continuously along the eastern boundary of North America from northern Canada to Cape Hatteras dividing the relatively cool, fresh water over the continental shelf from the warmer, saltier water over the continental slope. The Mid-Atlantic shelfbreak front is characterized by high biological productivity, large gradients in water-mass properties, and an energetic and unstable along-shelf jet. It is also a region with a large coastal population with pollution issues such as offshore dumpsites. Combined observations and models suggest large vertical velocities and significant cross-frontal fluxes of heat, salt, nutrients, carbon, and other materials. Transport and exchange influence water-mass characteristics, shelf-slope ecosystems, and mediate the role of the coastal ocean in global biogeochemical cycles.

The frontal structure varies spatially on scales of several to hundreds of kilometers and temporally on scales of days to weeks. The variability results from instabilities intrinsic to the frontal dynamics and external mesoscale features such as warm-core rings generated by the Gulf Stream. Different processes and modes of variability likely control the cross-frontal transport of particular substances; for example, onshore transport of nutrients almost certainly occurs differently than offshore transport of particulate carbon. The details of both processes have not been resolved in past studies and are poorly understood.

To effectively observe the wide range of spatial and temporal variability of the shelfbreak front, understand frontal fluid and ecosystem dynamics, and determine cross-frontal fluxes of physical and biogeochemical properties requires coherent, multi-disciplinary measurements in a "control volume" mode. The Pioneer Array will be an instrumented mooring array arranged to provide cross- and along-shelf observations from sea surface to seafloor, in high vertical and temporal resolution, and enhanced with instrumented AUVs and glider fleets. The moorings will support suites of meteorological sensors, and multi-disciplinary in-water and benthic sensors to provide detailed descriptions of the targeted shelf-slope area. In situ data from the Pioneer Array will be complemented by remotely sensed surface data and used to support advanced data assimilation and modeling. Analogs to this shelfbreak frontal system exist worldwide; the concept of the Pioneer Array and its results will have application beyond this first deployment.

Science Questions	Processes	Spatial Scale	Temporal Scale	Measurements Required	Sensors Required (Bold = Core sensor)	Sampling Requirements	Site(s) Required for Science	Experiment Description
What are the processes leading to the large heat, salt, nutrient, and carbon fluxes across the mid-Atlantic Bight shelfbreak front?	Atmospheric forcing, wind stress, air-sea exchange of heat, mass, gases, momentum.	*Horizontal:* Variable scales - meters to km; tens of km for atmospheric mesoscale processes. *Vertical:* Millimeter to 10s of meters.	*Air-sea interface:* Minutes to hours. *Water column:* Hours to days.	Specific humidity Barometric pressure Wind speed, direction, stress Shortwave radiation Longwave radiation Precipitation Surface wave spectra Air temperature Sea surface temperature Sea surface salinity pCO2 in air and sea surface (Δ pCO2) pH Dissolved oxygen	**Hygrometer** **Barometer** **Sonic anemometer** **Pyranometer** **Pyrogeometer** **Rain gauge** **Accelerometer, rate gyro** **Thermister** **CTD** **IR gas analyzer** **pCO2 analyzer** **pH** **DO**	Air-sea interface: Hourly to daily sampling Surface buoy with the power and data transmission to support meteorological instrumentation and near-surface sensors. The 2-way, near-real time communication to support adjustable spatial and temporal sampling to respond to episodic, short-term events or variable-scale phenomena. Time series spanning daily to inter-annual scales.	The Mid-Atlantic Bight has a broad continental shelf with a well defined shelfbreak front subject to non-linear instabilities, an along-shelf jet, and strong interactions with warm core Gulf Stream rings. The shelf-slope region is a site of substantial along- and cross-shelf fluxes of heat, freshwater, nutrients, and carbon occur. Shelfbreak fronts support high biological activity and elevated levels of primary and secondary productivity, including commercially important shell- and finfish. Research enabled by the **Pioneer and Endurance arrays** will provide for comparative studies of East Coast and West Coast continental shelves.	The **Pioneer Array** will be an instrumented mooring array arranged to provide cross- and along-shelf observations from sea surface to seafloor, in high vertical and temporal resolution, and enhanced with instrumented AUVs and glider fleets. The mooring array "backbone" will extend approximately 40 km in the cross-shelf direction and roughly 10 km along-shelf, and be centered on the shelfbreak front (based on climatology). Prior knowledge of the temporal and spatial correlation scales will be used to determine spacing of the moored array and sampling pattern of AUVs and gliders. The infrastructure will include surface moorings supporting suites of meteorological sensors, shallow in-water sensors, and connect to a multifunction benthic node providing connectivity to sensors and/or AUV docking station. Subsurface moorings will provide profiling capability from near bottom to the surface. Moorings, AUVs, and gliders will support suites of multi-disciplinary sensors to provide detailed descriptions of the targeted shelf-slope area. AUVs and gliders will enable adaptive sampling and extend spatial observations along-shelf and over the slope (100-300 km). AUV missions will focused on frontal processes. Gliders will survey the outer shelf and slope around the moored array. The **PNW Endurance Array** will be a mixture of cabled and uncabled instrumented moorings with surface buoys to support air-sea exchange and water column measurements across the continental shelf. Surface-piercing profiling moorings will monitor water column changes and material transport (e.g., nutrients, dissolved & particulate material) from nearshore to the deep ocean.
	Variability in water mass structure, cross-shelf gradients within the front, shelf/slope circulation, and along-front instabilities. Estimating cross-shelf fluxes.	*Vertical:* Sub-meter in upper 10 m to meters throughout the surface mixed layer; 10s of meters through the rest of the water column. *Horizontal:* 10s meters to 10s km.	*Water column:* Hours to days.	Density structure Horizontal velocity structure (shear), Vertical velocity Baroclinic, barotropic tides Penetrating solar radiation Optical attenuation & absorption Photosynthetically available radiation Chlorophyll-a Colored dissolved organic matter Particle optical characteristics Dissolved oxygen pH Nitrate Phosphate, Silicate	**Profiling CTD, Fixed and profiling current meters** **3-axis ADV, ADCP** **Multi-wavelength radiometer** **Multi-channel spectrophotometer** **PAR meter** **Chl-a & CDOM fluorescence** **Backscatter, transmissometer** **DO** **pH** **NO3 sensor** **PO4, Si(OH)4 analyzers** (on AUVs)	Profiling capability to support sampling at: Sub-meter in depths of 1-10 m. Sub-meter to 1-m intervals in mixed layer (to 200 m) 1-m intervals to bottom. Capability to operate in sampling mode over smaller and/or fixed depth intervals. Mixed layer profiles at ~3-hour intervals (note that sampling interval is depth dependent), with capability to adjust sampling frequency to respond to events and/or short-term phenomena. Instrumented AUVs and gliders with 2-way communications to expand high resolution spatial sampling. Time series spanning seasonal, annual, to decadal scales. Capability to accommodate future sensors (e.g., additional nutrient sensors, gas samplers, hyperspectral spectrophotometers, optical plankton detectors, etc.).		
	Estimated phytoplankton biomass. Estimated gross daily production. Seasonal variability in estimated net annual production.	*Vertical:* Sub-meter in upper 10 m to meters in the mixed layer; 10s meters throughout the water column. *Horizontal:* 10s meters to 10s km.	Days to weeks. Days to weeks. Days to years.	As above plus: Phytoplankton particle mass concentration Dissolved oxygen Photosynthetically available radiation. Optical attenuation & absorption	As above plus: **Transmissometer** **Chl-a fluor** **DO** **PAR meter** **Multi-channel spectrophotometer**			
	Bottom boundary layer dynamics. Community respiration.	*Vertical:* 1 to 10s m in near bottom layer. *Horizontal:* 10s meters to 100s m.	Minutes to days.	Profiles from seafloor to 100m of: Mean & turbulent current velocity Density structure Dissolved oxygen pH Optical attenuation & absorption Nitrate Particle optical characteristics	**ADCP** **Fixed 3-D ACM** **CTD** **DO** **pH** **Multi-channel spectrophotometer** **NO3 sensor** **Chl-a & CDOM fluorometer** **Backscatter, transmissometer**			
What is the relationship between the variability in the shelf-break frontal jet and along-front structure in phytoplankton distributions?	As above plus: Shifts in phytoplankton community structure.	*Vertical:* Sub-meter in upper 10 m to meters in the mixed layer; 10s meters throughout the water column. *Horizontal:* 10s meters to 10s km.	Days to years.	As above plus: Size distribution Spectral absorption Species abundance	As above plus: Imaging flow cytometer Optical plankton detector			
What aspects of Interannual variability (e.g., stratification, offshore circulation patterns, jet velocities, wind forcing) are most important for modulating shelf/slope exchange of dissolved and particulate materials?	As above plus: Distribution of Radium isotopes.	As above.	Days to years.	As above.	Ra collection system.	As above plus: Capability to support water filtration/preconcentration system.		

TRANSFORMATIVE CAPABILITIES

A movable, highly instrumented array to simultaneously resolve the small spatial scales of cross-front gradients and the larger scales of frontal instabilities. The combination of AUVs, gliders, and mooring array provides the spatial coverage and adaptive sampling of a ship with the temporal coverage of long-term mooring arrays.

Appendix B. Legend for Sensors Listed in Science Traceability Matrices

Measurement	Sensor	Acronym or Symbol	Core Sensor (x)
Surface Meteorology			
Air Temperature	Thermister		x
Atmospheric pressure	Barometer		x
Relative humidity	Hygrometer		x
Wind velocity	Sonic anemometer		x
Precipitation	Rain gauge		x
Short-wave solar radiation	Pyranometer		x
Long-wave solar radiation	Pyrogeometer		x
Partial pressure of carbon dioxide in air	Infra-red CO_2 gas analyzer	IR gas analyzer	x
Surface waves, motion	Accelerometer / rate gyro		x
Wind profiles	3-D Wind profiler		
Water Column			
Partial pressure of carbon dioxide in water	pCO2 analyzer	In-water pCO2	x
Dissolved oxygen	DO sensor	DO	x
Acidity or pH	pH electrode	pH	x
Temperature	Conductivity-Temperature-Depth	CTD	x
Salinity	Conductivity-Temperature-Depth	CTD	x
Pressure	Conductivity-Temperature-Depth	CTD	x
Mean current velocity	Acoustic current meter, Acoustic Doppler velocimeter	ACM, ADV	x
Mean current velocity profile	Acoustic Doppler Current Profiler	ADCP	x
Turbulent velocity	3-D Acoustic current meter	3-D ACM, ADV	x
Vertically averaged absolute water velocity, temperature, and pressure	Horizontal Electric Field Pressure Inverted Echo Sounder	HPIES	On RSN
Nitrate	NO3 wet chemical analyzer or ultra-violet spectrophotometric sensor	NO3	x
Ortho phosphate	PO4 wet chemical analyzer	PO4	Pioneer AUV
Silicate	Si(OH)4 wet chemical analyzer	Si(OH)4	Pioneer AUV
Penetrating solar radiation	Multi-wavelength radiometer		x
Chlorophyll-a fluorescence	Chl-a Fluorometer	Chl-a	x
Colored dissolved organic matter	CDOM fluorometer	CDOM	x
Suspended particulates	Optical backscatter	bb	x

Measurement	**Sensor**	**Acronym or Symbol**	**Core Sensor (x)**
Spectral optical absorption, attenuation	Multi-spectral spectrophotometer		x
Spectral transmittance	Transmissometer		x
Macrofauna, mineral precipitation observations	High/low-resolution Camera		x
Photosynthetically available radiation	PAR radiometer	PAR	x
Seismic, wind, rain, fish signals, marine mammal, ship activity,	Broadband acoustic receiver		x
Sound	Hydrophone		x
Phytoplankton abundance, size	Optical plankton detector, Imaging flow cytometer		
Plankton size distribution	Optical plankton detector, Laser optical plankton counters, Video plankton recorder		
Fish, zooplankton acoustic signals.	Multifrequency acoustic echosounder		
Microbial assemblage, concentration	Environmental sample processor	ESP	
Gas bubble size, distribution	Acoustic resonator		
Particle size distribution	Laser diffraction scattering size distribution	LISST	
Microbial cell optical imaging	Laser microscope		
Radium and other dissolved elements	Water filtration/concentration device		
Dissolved iron, manganese, speciation	Fe, Mn analyzer, mass spectrometer		
Seafloor			
Salinity, temperature, pressure, dissolved oxygen	CTD-O2	CTD-O2	x
Seismic events, slow tremor	Broadband seismometer		x
Seismic events, local fracturing, faulting, mammal tracking	Short-period seismometer		x
Pressure change, tidal perturbations	Differential pressure gauge		x
Vertical component of seismicity, mammal tracking	Hydrophone		x
Inflation, deflation of crust, tidal perturbations	Bottom pressure tilt recorder	BPTR	x
Temperature, chlorinity, dissolved H_2, acidity, dissolved H_2S	Temperature-resistivity- H_2 - H_2S-pH sensor		x

Measurement	**Sensor**	**Acronym or Symbol**	**Core Sensor (x)**
Dissolved major and trace elements, isotopes	*In situ* Time-series water sampler		x
Microbial characterization	Particulate DNA sampler		x
Plume velocity structure	Acoustic Doppler Current Profiler	ADCP	x
Temperature distribution	Thermister arrays		x
Permeability, fluid convection in crust	Subseafloor flow sensor		x
Production of gasses	Mass spectrometer		x
Seismic events	Strong motion accelerometer		
Seafloor strain	Interferometric fiber optic strainmeter		
Seafloor strain	Direct path acoustic strainmeter		
Microbial assemblages (in chimneys and sediments)	*In situ* microbial incubators, *in situ* DNA sensors		
Microbial distribution	*In situ* flow cytometer		
Dissolved mineral, gas species	Raman spectrometers		
Plume or acoustic bubble imaging	Sonar		
Subseafloor measurements of temperature, resistivity, physical properties, pore fluid pressure, chemistry, etc.	Circulation Obviation Retrofit Kit	CORK	
Subseafloor measurements of temperature, resistivity, physical properties, pore fluid pressure, chemistry, etc.	Simple Coned Instrument for Measuring Parameters *In Situ*	SCIMPI	