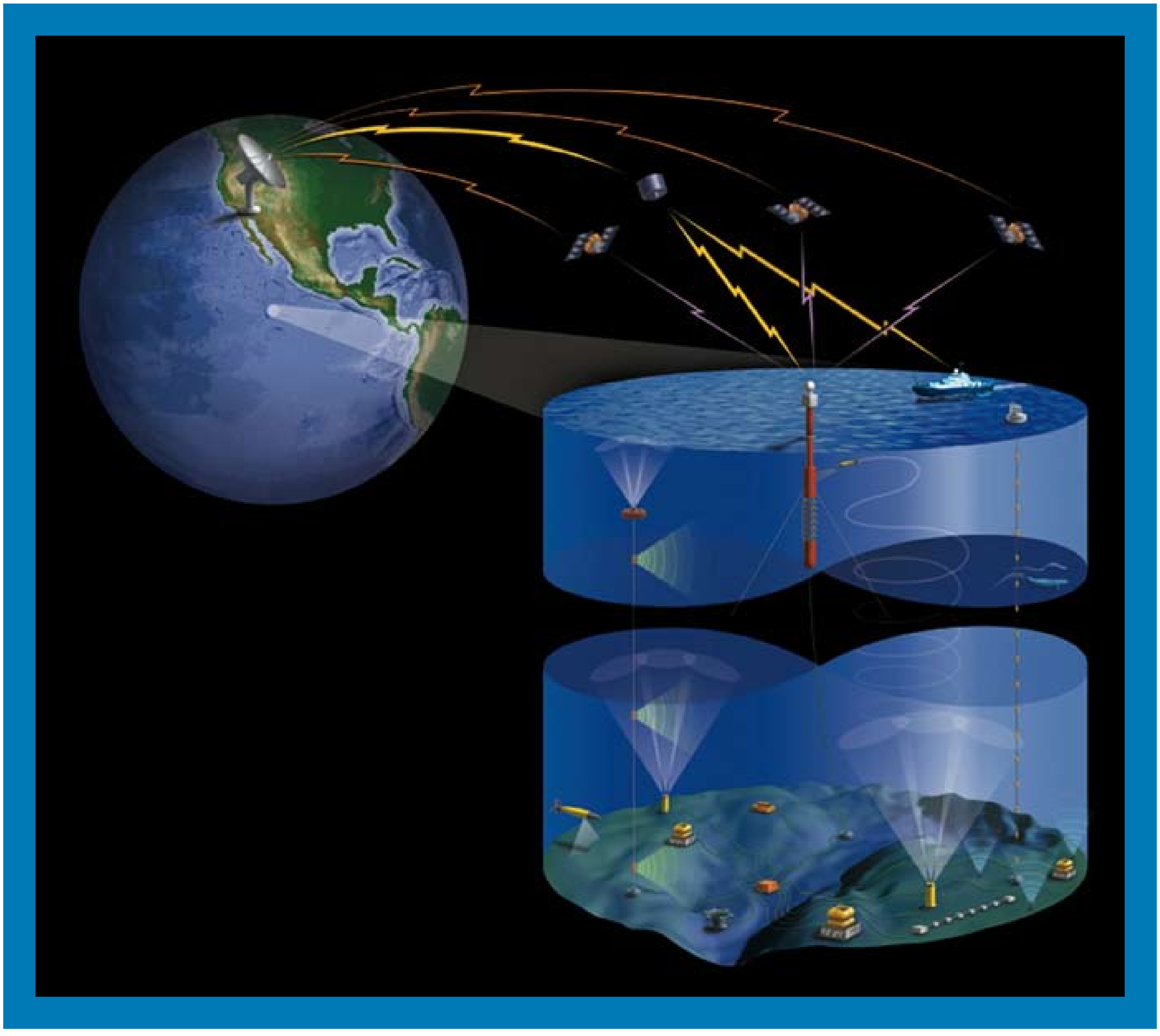
Ocean Observatories Initiative (OOI) Scientific Objectives and Network Design



ocean research interactive
ORION
observatory networks

July 2006

NSF

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Preface

The National Science Foundation's Ocean Observatories Initiative (OOI), part of the research-driven Ocean Research Interactive Observatory Networks (ORION) Program, is a major contribution by NSF to a broader national and international effort to establish a global Earth observing system, the Global Earth Observation System of Systems (GEOSS). The underlying goal of the OOI, and the ORION Program, is to develop the new knowledge and technologies that will advance our understanding of fundamental ocean and Earth processes. The OOI will deliver an advanced, interactive, distributed sensor network, with an operational lifetime of 25-30 years, for studies in locations ranging from the coastal waters of North America to the remote Southern Ocean. A system-wide cyberinfrastructure will deliver data in near-real time to a scientist's desktop from almost anywhere in the world's oceans, as well as allow users to remotely control their instruments, perform in situ experiments at observatory sites, and construct virtual observatories of suites of sensors specifically tailored to their scientific needs. The OOI promises to transform the ocean sciences in the coming decade by opening entirely new avenues of research, encouraging the development and application of new sensors and technologies, providing new opportunities to convey the importance of the oceans to students and the general public, and providing essential information for decision-makers responsible for developing ocean policy.

The purpose of this document is to describe examples of high priority science questions within the broad science themes posed in the OOI Science Plan published in 2005 that will be investigated using the OOI infrastructure at the sites described in the OOI Conceptual Network Design (CND). Opportunities span all disciplines of the ocean sciences. The examples given here illustrate how continuous observations and interactive experiments provided by ocean observatories are required in order to make significant progress in many areas of the ocean sciences. Where appropriate, research questions that can be addressed across all scales of the infrastructure (global, regional, coastal) are noted. In addition, we highlight some examples of observatory-based research that are anticipated to lead to early success and/or lead to major advances in our understanding of ocean and Earth processes.

This document was prepared under the guidance of the Steering Committee of the ORION Program and the ORION Program Office. An ad hoc writing committee, chaired by Jim Yoder (Woods Hole Oceanographic Institution) and including Ginger Armbrust (University of Washington), Kendra Daly (ORION Program Director), Robert Detrick (Woods Hole Oceanographic Institution), Steve D'Hondt (University of Rhode Island), Rick Jahnke (Skidaway Institute of Oceanography), Doug Luther (University of Hawaii), Oscar Schofield (Rutgers University) and Anne Trehu (Oregon State University) prepared this document for review by an NSF-appointed "Blue Ribbon Review Panel". It draws heavily from the OOI Science Plan and the CND prepared by ORION's Science and Technical Advisory Committee (STAC, Chair Doug Luther) with input from ORION's Engineering (Chair Keith Raybould, Monterey Bay Aquarium Research Institution), Cyberinfrastructure (Chair Larry Mayer, University of New Hampshire), Sensors (Chair Scott Gallager, Woods Hole Oceanographic Institution) and Education and Public Awareness (Chair George Matsumoto, Monterey Bay Aquarium Research Institution) committees. We especially want to thank the chairs of the STAC subcommittees that prepared the CND for text and figures used in this document. They include John Collins (Woods Hole Oceanographic Institution), Deb Kelley (University of Washington), Collin Roesler (Bigelow Laboratory), Uwe Send (Scripps Institution of Oceanography), John Trowbridge (Woods Hole Oceanographic Institution) and William Wilcock (University of Washington).

1. Vision and Motivation for the OOI

The quality of life on Earth is strongly affected by the ocean, which covers two-thirds of our planet. The ocean modulates both short and longer-term variations in climate, harbors major energy and raw material resources, contains and supports the largest biosphere on Earth, significantly influences rainfall and temperature patterns on land, and occasionally devastates heavily populated coastal regions due to storms or tsunamis. More than a century and a half of ship-based observations and research has described the basic features and processes operating in the ocean and their interactions with terrestrial and atmospheric systems. The delineation of major ocean circulation patterns, the development of plate tectonics, the discovery of the bacteria and archeae that dominate open ocean biogeochemical processes, and documentation of the coupled ocean-atmospheric interactions that lead to the El Niño-Southern Oscillation (ENSO) are all major achievements of the ocean sciences over the past five decades.

Yet, as our understanding of the oceans has advanced, it has become increasingly apparent that many critical processes occur at temporal and spatial scales that cannot be effectively studied using only traditional tools such as ships, moorings, drifters, and satellites. Ship-based studies, for example, are very limited in their ability to investigate episodic events or to study dynamic systems that change over very short time periods (seconds to hours) or over time periods longer than a few months. While satellite observations have provided a unique, synoptic global perspective of the ocean, they remain primarily limited to measuring properties at the air-sea interface and in the uppermost ocean.

The National Science Foundation's Ocean Observatories Initiative (OOI) is designed to enable powerful new scientific approaches for investigating complex ocean-atmosphere-Earth interactions. The OOI will transform ocean research by developing pioneering new technology and establishing a network of interactive, globally distributed sensors and instrumentation for the research-driven Ocean Research Interactive Observatory Network (ORION) Program. Recent technological advances in sensors, low-power and miniaturized electronics, in situ genomic analyses, satellite and fiber optic communications, high-definition imaging, robotics, and data assimilation-modeling-visualization are opening entirely new opportunities for in situ experiments and investigations of ocean processes changing over time periods of seconds to decades. The OOI will enable innovative new studies of ocean and Earth processes, and foster technological innovation that will contribute to maintaining American leadership in scientific advancement and the global economy, as well as provide unprecedented educational opportunities.

The purpose of this document is to describe examples of high priority science questions within the broad science themes posed in the OOI Science Plan that will be investigated using the OOI infrastructure at the sites described in the OOI Conceptual Network Design (CND). While we have emphasized some expected scientific returns from the OOI, we also recognize that the novel technology provided by the OOI will lead to scientific exploration and new discoveries not yet imagined.

2. OOI Science Themes

The OOI Science Plan, published in 2005, outlined five major science themes that were representative of the breadth of ocean research that will be enabled by the OOI infrastructure and supported through the ORION Program.

Climate Variability, Ocean Food Webs, and Biogeochemical Cycles

The impact of human activity on Earth's climate and its marine ecosystems is one of the overarching scientific questions of our time. Human activity has altered the Earth's biogeochemical cycles through massive releases of greenhouse gases (e.g., CO_2), the synthesis and mobilization of nutrients (N and P) and associated biogenic elements (S), and by the harvesting of many top predators within coastal and open-ocean ecosystems. The ocean plays a critical role in the Earth's response to climate change by providing a sink for CO_2, absorbing heat from the atmosphere and redistributing it through ocean currents, processing nutrients and contaminants, and changing sea level. Examples of key scientific questions for which observatories are anticipated to supply critical information include:

- *What is the ocean's role in storing anthropogenic carbon?*
- *How will ocean acidification due to rising atmospheric CO_2 levels affect marine ecosystems and food webs?*
- *What is the magnitude and cause of recent sea level rise and how rapidly will it rise in coming decades?*
- *Can we detect and predict the influence of longer-term climate change on ocean food webs in the presence of low frequency climate cycles?*

Our understanding of global climate dynamics is limited by our knowledge of the interactions between the ocean, atmosphere, and land. These interactions are affected by the numerous modes of climate variability, such as the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Pacific Decadal Oscillation (PDO) that alter the transport of heat, salt, carbon and nutrients. Furthermore, many critical processes such as cross-isopycnal mixing at ocean boundaries and at rough topography, as well as exchanges across frontal interfaces such as those found at many shelf-breaks, may occur aperiodically on interannual or even shorter time scales. Until our understanding of such processes is improved, interpretation of trends in ocean properties, potential ecosystem responses, and feedbacks on the climate system will be limited. Understanding the processes that underlie these phenomena requires high frequency, sustained measurements from coastal, regional, and global observatories coupled to physical-chemical-biological numerical models.

Coastal Ocean Dynamics and Ecosystems

Coastal systems have been highlighted as a research theme by OOI because most human-ocean interactions occur in the coastal zone and many important processes are concentrated and intensified at ocean-continent boundaries. Greater than 90% of the world's fish catch is harvested from coastal waters that also support major recreation and maritime industries. Chemical transport across the coastal ocean exerts a dominant control on major global geochemical cycles determining, for example, material exchange between the terrestrial and oceanic realms. Because >50% of the human population resides near coasts, understanding marine-related hazards is of particular importance.

While continental shelves represent approximately 8% of the ocean's surface area, they support approximately 30% of marine primary production. Additional factors, such as enhanced water stratification due to fresh water input, high rates of respiration and diverse sedimentary environments, create a patchwork of unique habitats that dominate critical biogeochemical processes such as removal of biologically-available nitrogen via denitrification and provide important nursery grounds for living marine resources. As a result, coastal systems play disproportionately important roles in the ecology and biogeochemistry of the oceans. To further understand and manage these important systems, we are faced with numerous specific research challenges. Examples include elucidating the external forcings and internal marine processes that control water quality

Figure 1. A harmful algal bloom of the dinoflagellate Noctiluca scintillans, known as a red tide. There is a growing sense that blooms of toxic algae are occurring more frequently, are lasting longer, and are spreading to more places possibly due to human influence. However, the conditions that trigger the occurrence and severity of harmful algal blooms remain poorly understood. Ship-based sampling strategies alone cannot capture the time and spatial variability of the processes responsible for these outbreaks. Sustained observations in the coastal ocean are required to detect these episodic, short-term events and resolve longer-term trends.

(e.g., formation of hypoxia); recruitment of marine organisms; benthic and water column habitats; invasion of harmful algal species (Fig. 1); and the occurrence of hazards to life and property (e.g., coastal inundation). Most of these phenomena reflect the combination and interaction of multiple processes.

Making this task more difficult is the realization that the relevant processes operate on a wide spectrum of space and time scales. A significant advancement in understanding coastal processes will require a continuous, distributed observational presence to detect episodic, short-term events and to resolve longer-term trends. Establishing this observational presence in representative eastern and western boundary current systems of North America and other representative shelf environments will maximize advances in our understanding. Examples of key scientific questions include:

- *What processes determine the transport of carbon, nutrients, planktonic organisms and other materials within the coastal ocean ecosystem?*
- *What conditions trigger the occurrence of harmful algal blooms and regime changes in the species composition of coastal ecosystems?*
- *What mix of physical and biological processes lead to hypoxic conditions in the coastal ocean?*

Turbulent Mixing and Biophysical Interactions

Turbulent mixing occurs over a broad spectrum of time and space scales and plays a critical role in the transfer of materials within the ocean and in the exchange of energy and gases between the ocean and atmosphere. Horizontal and vertical mixing within the ocean have a profound effect on a wide variety of biological processes, including phytoplankton community structure, cycles of primary productivity in the upper ocean, predator-prey interactions, larval dispersal, and the transfer of organic material to the deep sea. Turbulence in the bottom boundary layer plays an important role in determining benthic community structure, cross-shelf sediment transport, and the sequestration of organic material in sediments. A better understanding of turbulent flow, from the ocean surface to its bottom, is essential for developing improved models of processes ranging from large-scale ocean circulation to local ecosystem dynamics.

While important advances have recently been made in measuring small- and mesoscale-turbulence, these processes remain extremely difficult to study. First, turbulent flow in the oceans encompasses a wide range of scales from essentially the molecular level to mesoscale eddies having dimensions of tens to hundreds of kilometers. Second, the dynamics of turbulent flow are inherently unstable and non-linear, resulting in a strong intermittency and complexity in the flow. Third, the response of ecosystems to changes in their physical environment (nutrient levels, turbidity and light, biomechanical stresses) are themselves non-linear and complex. As a result, high-resolution, long time-series observations are needed to characterize statistical measures of these processes. However, obtaining continuous, simultaneous information on mixing and responses at the required spatial resolution (mm to 10s or 100s of km) and temporal range (seconds to decades, to resolve the turbulence itself, and to deal with changing seasonal and interannual contexts) is simply not feasible using conventional ship-based expeditionary studies.

Measurements from mobile platforms and ships will be integrated with those from fixed observatories to examine such questions as:

- *What is the role of vertical mixing in the ocean interior for determining the global distribution of heat and nutrients in the ocean?*
- *What factors control the development of the mixed surface layer, the entrainment of stratified waters into the mixed layer and the exchange of gases between the mixed layer and the atmosphere?*
- *What is the role of vertical and horizontal mixing in determining plankton community structure in the upper ocean?*
- *How is benthic community structure affected by near-bottom turbulent events?*

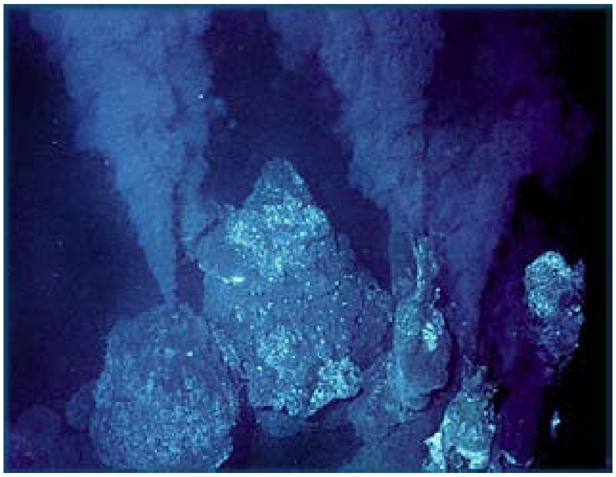


Figure 2. Mid-ocean ridge hydrothermal systems, and their associated biological communities, are thermally driven by episodic volcanic events, including dike intrusions and submarine eruptions. The flow rates and chemistry of these vents can remain stable over many years or can change rapidly over days or weeks. The only means of studying these systems is to install infrastructure and sensors necessary to detect transient events, and to provide the capability to adaptively measure and remotely sample the changes induced by volcanic or tectonic events.

Fluid-Rock Interactions and the Sub-Seafloor Biosphere

The upper oceanic crust comprises the largest aquifer on Earth. Fluid circulation within this aquifer influences the thermal state and composition of oceanic plates and interacts with hot, newly emplaced volcanic crust at mid-ocean ridges and at back-arc spreading centers to form spectacular "black smoker" hydrothermal vents with their unique biological communities (Fig. 2). On ridge flanks, and along continental margins, these fluids react with ocean crust and sediments at lower temperatures, slowly altering their composition and concentrating massive reservoirs of methane and methane hydrates along continental margins. The chemical changes associated with these fluid-rock interactions play important roles in controlling ocean chemistry while nutrients in these fluids sustain a vast, microbial biosphere below the seafloor that is just beginning to be explored.

Fluid flow through the thick sedimentary sequences that accumulate at both active and passive continental margins is driven by a wide range of factors, including sediment compaction and compression, tides, and density contrasts related to fluid composition. This flow results in widespread deposits of gas hydrates and low-temperature fluid seeps and gas vents along the margin that support biological communities that are distinct from those at hydrothermal vents. The extent and temporal evolution of vents and linkages between the ocean and the terrestrial hydrosphere are poorly documented and understood but are likely of critical importance to coastal ecosystems. These low temperature systems are now recognized to be widespread and of potential critical importance to coastal ecosystems. Subsequent mechanical dewatering and metamorphic dehydration of the oceanic crust and upper mantle due to temperature and pressure increases as the lithosphere is subducted has a major impact on generation of volcanoes and on earthquake processes and hazards along convergent margins and in the adjacent tectonic plates.

The overall geological, chemical and biological significance of both high and low temperature hydrothermal systems is still largely unknown. Fundamental questions exist regarding how ridge-crest hydrothermal systems, and the biological communities they support, are affected by episodic volcanic and tectonic events, the processes controlling the formation and dynamics of gas hydrates and their climatological significance, the depth and extent to which life may occur within the seafloor and overlying sediments, and the linkages between submarine plate-tectonic and sedimentary processes and this sub-seafloor biosphere. Similarly, the dynamics of flow and biological communities within shallower permeable sediments is mostly unexplored. However, there is increasing evidence that transient events – earthquakes, volcanic eruptions, massive slope failures, and storms – play a critical role in many different environments including mid-ocean ridges, passive and active continental shelves and slopes, and in the fore-arc and back-arc regions of subduction zones. Advancing understanding of the linkages and feedback mechanisms among geological, chemical, and biological processes within these highly dynamic environments will only be achieved through the use of long-term, in situ observatories on and beneath the seafloor with the capability to detect, respond, sample, and measure the major processes involved.

Examples of questions that can be addressed include:

- *What is the extent, abundance, distribution and diversity of the sub seafloor biosphere?*
- *How do submarine hydrothermal systems, and their associated biological communities, vary over time?*
- *What are the limits of life in these extreme environments?*
- *What processes control the formation and destabilization of gas hydrates?*
- *What role do gas hydrates play in catastrophic slope failure?*
- *How do seawater-groundwater interactions control biogeochemical cycling on continental shelves?*

Global Earth Structure and Plate-Scale Geodynamics

Plate tectonics has revolutionized our understanding of the dynamics of the Earth's surface, including such aspects as the formation of ocean basins, mountain building, rifting of continents, and the global distribution of earthquakes and volcanoes. This scientific revolution had a profound impact on society, explaining why and where earthquakes occur, providing a conceptual framework for determining where new oil and gas reservoirs are likely to be found, and helping us understand the pattern of volcanic activity observed at Earth's surface. While plate tectonics has been enormously successful at providing a quantitative description of the past motions of continents and a kinematic model of present-day tectonics, there are many fundamental questions regarding global and plate-scale geodynamics that remain unanswered, including the composition and dynamics of the Earth's deep interior, the origin of Earth's magnetic field, how plate boundaries interact and deform, stress redistribution following large earthquakes, and the links and feedbacks that exist among tectonic, magmatic, hydrothermal and biological processes along active plate boundaries.

Progress in addressing these important questions has been limited by two major factors: (1) the difficulty of making sustained geophysical observations over the 70% of Earth's surface beneath the ocean; and (2) the inability to instrumentally "capture" episodic, short-lived events such as earthquakes or volcanic eruptions along plate boundaries, most of which lie beneath the ocean. Although many of the instruments needed to make these measurements exist (e.g. hydrophones, seismometers, pressure sensors, and geodetic instrumentation), the deployment of these sensors in the ocean has typically lasted only a few weeks or months, instead of years, because of the limited power of autonomous, battery-operated instruments. Without a means of telemetering data from these instruments to shore in real time or near-real time, episodic events could only be detected long after they occurred, precluding any effort to study their immediate aftermath by deploying additional sensors or to take appropriate action if these events posed a threat to coastal populations.

OOI infrastructure will support long-term observations that will be able to address questions such as:

- *What is the physics of earthquake nucleation and rupture propagation for different types of plate boundaries (subduction zones, transforms, spreading centers)?*
- *How does the oceanic crust form?*
- *What is the interaction between volcanic, tectonic and hydrothermal processes in geologically active regions?*
- *What is the pattern of convection in the Earth's mantle and the origin and scales of mantle heterogeneity?*
- *What are the properties of Earth's core, core-mantle boundary and lowermost mantle?*

3. Summary of the OOI Conceptual Network Design

The OOI has three major components:

(1) an open-ocean distribution of deep-water moored buoys to address planetary-scale processes, especially in the more remote and inaccessible parts of the global ocean;

(2) a regional cabled observatory (RCO) that will provide unprecedented levels of power and bandwidth to sensors in the water column, and

on and below the seafloor spanning an entire tectonic plate; and

(3) a suite of permanent and relocatable assets to study the dynamics of the coastal ocean of North America.

These three elements will be integrated into a single "system-of-systems" by a network-wide cyberinfrastructure that will deliver data in near-real time to a scientist's desktop from almost anywhere in the world's oceans, as well as allow users to remotely control their instruments, perform in situ experiments at observatory sites, and construct virtual observatories of suites of sensors specifically tailored to their scientific needs.

The ORION Science and Technical Advisory Committee (STAC), working with the ORION Engineering and Sensor Committees and the ORION Program Office, has developed a Conceptual Network Design (CND) for the OOI. The CND is based on dozens of workshops and planning documents dating back to the late 1980s. A major input to the CND was proposals submitted to a Request for Assistance (RFA) issued by the ORION Program Office in January 2005 in cooperation with NSF's Division of Ocean Sciences. The submission of 48 RFA proposals, representing the thoughts and ideas of more than 550 investigators, and the involvement of over 130 separate research and educational institutions, attests to the exceptional level of interest and enthusiasm on the part of the U.S. oceanographic community for observatory-based ocean science. A review panel comprised of scientists with no connection to any RFA proposal was convened by NSF in September 2005 to evaluate the RFA proposals and provide a binning based on the importance and uniqueness of the proposed research, the adequacy of the experimental plans, the readiness of the experimental designs and proposed technologies, and the innovative use of the OOI infrastructure.

A preliminary version of the CND was posted on the ORION web site in March 2006 and presented at the ORION Design and Implementation (D&I) Workshop on 27-30 March 2006 for discussion and evaluation by the more than 280 ocean scientists who attended the meeting. Utilizing the recommendations developed at the D&I Workshop (*http://www.orionprogram.org/di_workshop.html*), and revised cost estimates developed by the ORION Engineering Committee, the STAC revised and finalized the CND in May and June 2006. This was an extraordinarily difficult task given the excellence of the proposed science across all disciplines and their associated infrastructure requirements which would have claimed several times the resources currently available through the OOI. This section presents a brief summary of the revised plans. The complete CND is available on the ORION website at *http://www.orionprogram.org/capabilities/cnd.html*

OOI Coastal Observatory

The OOI Coastal Observatory experimental design has three major elements:

(1) a permanent West Coast Endurance Array concentrated in the Pacific Northwest (PNW) with complementary assets off California,

(2) a permanent East Coast Endurance Array located in the South Atlantic Bight (SAB) off the southeast U.S., and

(3) a moveable Pioneer Array that will be initially located in the Mid-Atlantic Bight (MAB) region off southern New England to study processes at the shelf-break front.

The West Coast and East Coast Endurance Arrays capitalize on the contrast between: (i) a narrow shelf (off the West Coast) forced by seasonal, upwelling-favorable winds, a large buoyancy source and an eastern boundary current and (ii) a broad shelf (off the East Coast) forced by a western boundary current, distributed buoyancy sources and extreme wind events.

The two endurance arrays, therefore, provide the opportunity to address complementary interdisciplinary scientific questions in contrasting systems representing two canonical classes of coastal margins with numerous analogs worldwide. Furthermore, both systems are affected by the ocean climate system with El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) more important on the West Coast, and the North Atlantic Oscillation (NAO) on the East Coast. The interan-

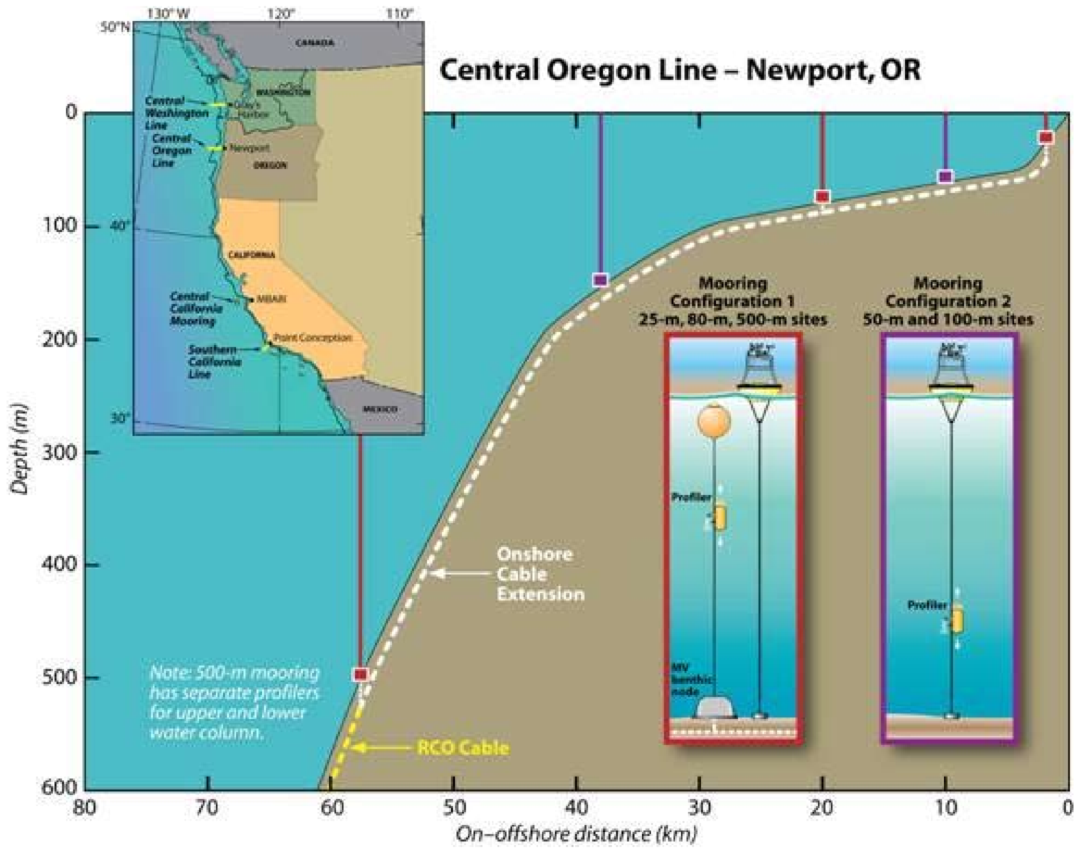


Figure 3. Map of the West Coast Endurance Array (inset) with schematic diagram of the Central Oregon line. The West Coast coastal observatory consists of a Central Washington Line, a Central Oregon line, a Central California mooring, a Southern California line, and a glider array (not shown). The Central Washington and Central Oregon lines will each consist of five moorings, positioned to determine cross-margin variability, the variability of cross-margin transports, and the characteristics of the buoyant discharge from the Columbia River. At the Central Oregon Line, the RCO cable will be extended onshore from Node N1 (Fig. 6) to the 25-m isobath. Benthic nodes will be connected to the cable at the 25-m, 80-m and 500-m isobaths, and these sites will be equipped with cabled surface profilers and independent surface moorings to support meteorological sensors. Surface moorings with profilers will occupy the 50-m and 150-m sites. The Central California line will include a mooring on the Monterey Accelerated Research System (MARS) cable, an NSF-sponsored test-bed for ORION's cabled observatories and instrumentation. The Southern California line will consist of shelf and slope moorings. Instrumentation and glider transects are not shown.

nual and longer-period variability associated with the ocean climate system link the coastal margins with processes that originate in, and also affect, the open ocean. The Pioneer Array proposed as part of the coastal OOI coastal design will employ adaptive sampling strategies to resolve multiple temporal and spatial scales in a variety of coastal settings.

The OOI coastal observatories will provide an unprecedented opportunity to address broad classes of critically important coastal oceanographic problems. These include, in particular, shelf-ocean exchange, air-sea transport, benthic processes and benthic-pelagic coupling, transport and transformations of terrestrial discharges, response to extreme events, biogeochemical cycling, harmful algal blooms, hypoxia, and ecosystem dynamics.

West Coast Endurance Array - The proposed West Coast Endurance Array (Fig. 3) consists of the following:

(1) an uncabled line of four shelf moorings and one slope mooring off Grays Harbor in Central Washington;

(2) four shelf moorings and one slope mooring on an existing long-term sampling line off Newport, Oregon, three of which will be cabled by means of an onshore extension of the OOI Regional Cabled Observatory (RCO; see node N1 in Fig. 6);

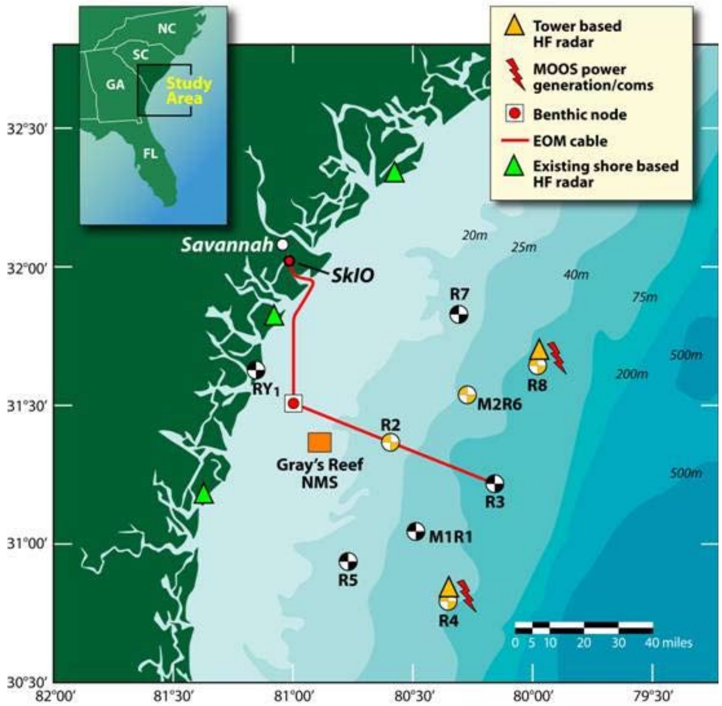


Figure 4. Map showing the elements of the South Atlantic Bight (SAB) Endurance Array. R2, R3, R4, R5, R7, R8, M1R1 and M2R6 are existing Navy towers, some of which are components of the ongoing SEA-COOS and SABSOON programs. The seafloor cable will extend from a shore landing near Skidaway Institute of Oceanography to a seafloor node near 31.5°N, 81°W and then to towers R2 and R3, which will be equipped with air-side (dry) nodes, benthic nodes, and water-column profilers (not shown). High-frequency (HF) radars will be placed on towers R4 and R8, which will complement existing shore-based HF radars, and Monterey Ocean Observing System (MOOS) units will be placed on towers R4 and R8 for power and two-way communications. Glider transects (not shown) will complement the fixed assets.

(3) a mooring at the cabled Monterey Accelerated Research System (MARS) node in Central California;

(4) an uncabled line with one slope and one shelf mooring in the Southern California Bight; and

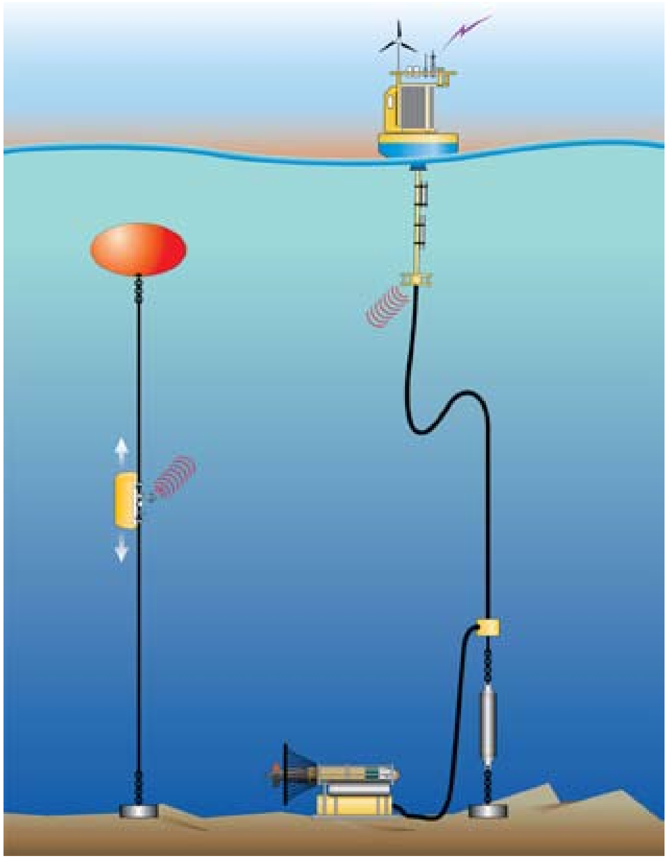
(5) an array of gliders.

The basic components of the infrastructure in this West Coast Endurance Array (as well as in the other two coastal elements of the CND) are surface buoys with capabilities for power generation and satellite communications, electro-optical-mechanical (EOM) moorings to provide power and communications to the seafloor, mechanical moorings with acoustic communication delivery, profiling moorings with real-time communications and battery re-generation capabilities, low-voltage (LV) and medium-voltage (MV) benthic nodes, seafloor cables, gliders, autonomous underwater vehicles (AUVs), and core instrumentation.

The assets in the West Coast Endurance Array are concentrated along the Central Oregon and Central Washington lines. The purposes of these lines are to contrast shelf and slope processes in regions influenced differently by the outflow from the Columbia River (e.g., the coastally attached northward plume off Washington during downwelling events and the detached south-southwest plume off Oregon during upwelling events) and to contrast processes in a region of smooth topography (i.e., the Washington shelf) and a region with a topographic bank (i.e., Heceta Bank on the Oregon shelf). The moorings on the Washington and Oregon lines will include highly capable installations with full-depth water column profiling, surface expressions for atmospheric measurements, and benthic nodes for intensive near-bottom measurements at the 25, 80 and 500-m isobaths, in addition to less capable installations without benthic nodes at the 50 and 150-m isobaths. The shelf and slope moorings on the Washington and Oregon lines will be complemented by offshore infrastructure associated with the RCO.

The objectives of the moorings off Central California and in the Southern California Bight are to sample different biogeographical regimes and to provide spatial measurements of northward-propagating disturbances (ENSO-forced) originating in the tropical Pacific, which will aid in the interpretation and analysis of the more densely sampled measurements in the Pacific Northwest. The OOI assets off Central California will capitalize on the cabled MARS node and will add a full-depth profiling capability to this facility. An array of gliders will be initially deployed to characterize shelf-wide features. Over time, a subset of the gliders will be allocated to characterize smaller-scale features, in a process informed by measurements and modeling.

East Coast Endurance Array - The main element of the South Atlantic Bight (SAB) East Coast Endurance Array (Fig. 4) is a cable extending from shore to a medium-voltage inner shelf benthic node and then to dry and wet nodes on a mid-shelf tower (R2) and finally to dry and wet nodes at a shelf-break tower (R3). The inner shelf node will be equipped with a full-water-depth profiling capability. Each of the cabled towers will have a cabled profiling capability remote from the tower (by approximately 1 km) to minimize flow disturbances and reef effects associated with the towers. Two additional uncabled towers (R4 and R8) will be instrumented with high-frequency (HF) radars, provided with power and two-way communications by Monterey Ocean Observing System (MOOS) packages to measure surface currents over the outer shelf and slope. Observations from an array of gliders will be used to quantify spatial variability.



Pioneer Array - The coastal Pioneer Array employs fixed moorings, profiling moorings, and adaptive sampling by means of gliders and autonomous underwater vehicles (AUVs) to produce synoptic samples of multi-scale coastal oceanographic phenomena. The array consists of four electro-optical-mechanical (EOM) moorings with surface expressions and capabilities for local power generation and satellite data transmission, five subsurface profiling moorings with internal power and acoustic telemetry capabilities, four acoustic repeater moorings with internal power, three long-range (~400 km) AUVs, two AUV docking stations, twelve gliders (~ one month duration), and core instrumentation. In the configuration contemplated at present (Fig. 5), two EOM moorings are dedicated to bottom-mounted AUV docking stations, and two are dedicated to fixed sensors. The subsurface profiling moorings transmit data by means of the acoustic repeaters (where necessary) to the EOM moorings for satellite transmission. The AUVs sample spatially in response to two-way communications and obtain power and transmit data by means of the docking stations. Glider operations are handled by ship.

The initial location of the Pioneer Array is planned for the shelf-break front of the Mid-Atlantic Bight (MAB), off southern New England. This site was chosen because of the compelling, high priority science that can be done here and because of the complexity of the array, which dictates that its first application should be in the environment for which it was originally designed. Because of the developmental nature of AUV docking operations, espe-

Figure 5. Schematic diagram of elements of the Pioneer Array. EOM moorings (with surface expressions equipped with capabilities for power generation and satellite transmissions) provide power and two-way communications to an AUV fleet by means of a bottom mounted docking station, while also providing two-way communications to a sensor suite on a nearby internally powered profiling mooring, by means of acoustic telemetry. Elements of the array not shown here include EOM moorings (with surface expressions equipped with capabilities for power generation and satellite generation) that are devoted to instrumentation on the mooring itself, repeater moorings for longer-range acoustic transmissions, and gliders for spatial sampling that complement the AUV measurements.

cially at moorings, plans call for the AUV dock to be deployed initially at the nearby Martha's Vineyard Coastal Observatory. The array will span approximately 50 km and 40 km in the along- and cross-front directions, respectively. AUVs will sample within the front and over the shelf, and gliders will sample the slope water.

OOI Regional Cabled Observatory (RCO)

The OOI Regional Cabled Observatory (RCO) is a plate scale experiment of unparalleled scope that is focused on integrated investigations extending from the sub-seafloor biosphere across the benthic boundary layer through the entire ocean water column to the sea surface-atmosphere interface. Spatially associated with the Juan de Fuca tectonic plate (Fig. 6), the RCO will enable in-depth study and decadal time–series observations of globally significant oceanographic and Earth processes expressed regionally – including biogeochemical cycles, climate forcing of ocean dynamics, the carbon cycle, fisheries, earthquake and tsunami hazards, life in extreme environments, and plate tectonic processes. Dense spatial and temporal sampling, coupled with interactive capabilities will allow the ocean science community, for the first time, to make fundamental measurements and exciting discoveries about processes that occur over centimeter to 100's of kilometer distances, and at seconds to decade time scales.

The RCO experimental design is shown in Figure 6. The northern loop (Stage I) of the RCO is being constructed by the University of Victoria with CAN $62.4M

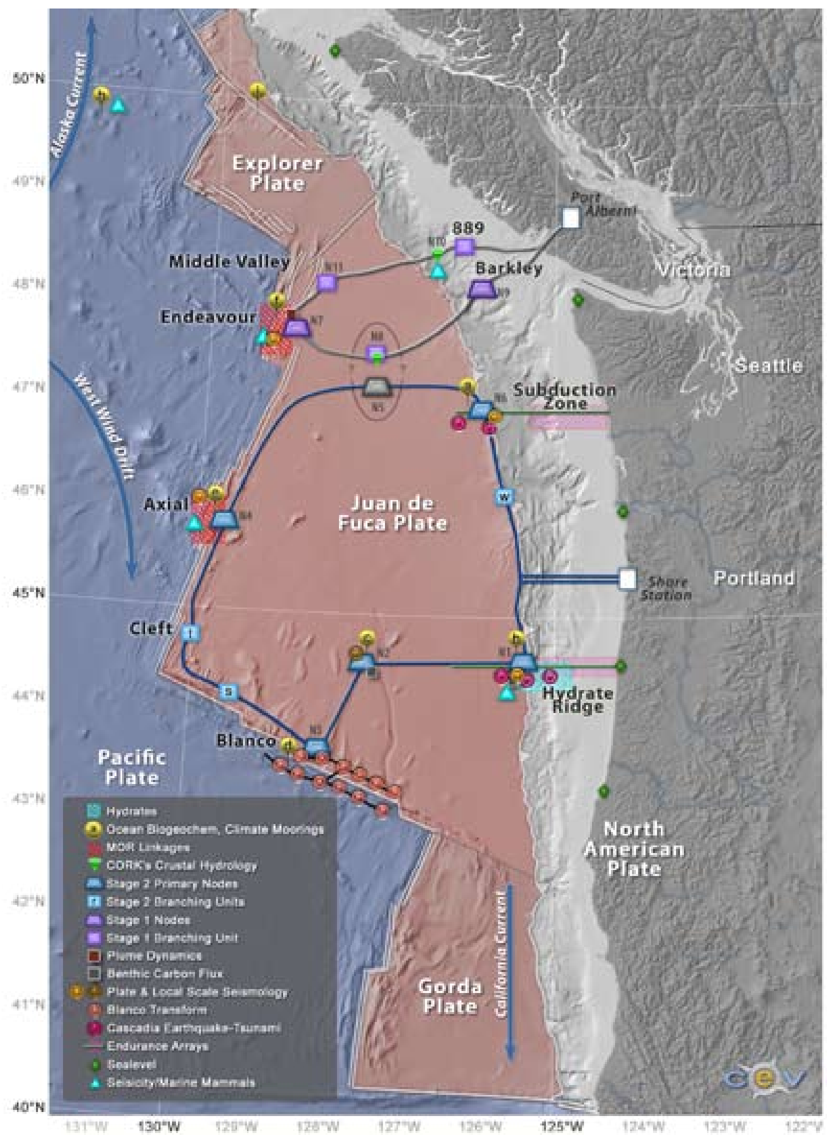


Figure 6. Regional cabled observatory (RCO) integrated experimental design. This plate scale experiment will be installed in two stages. The northern loop (Stage I) of the RCO is being constructed by the University of Victoria with funding from the Canadian Foundation for Innovation and the British Columbia Development Fund and is slated for installation in 2007. Stage II of the RCO (southern loop), which will be funded through NSF's OOI, will include 5 primary nodes, 6 branching units for future expansion and 9 full water column moorings connected by 1490 km of fiber optic cable.

funding from the Canadian Foundation for Innovation and the British Columbia Development Fund. The Stage I northern loop will have up to six instrumented nodes (the current baseline design is for two instrumented nodes and two expansion nodes). Stage I is slated to begin installation in 2007. The current design of Stage II of the RCO (southern loop), which will be funded through the OOI, includes 1490 km of electro-optical backbone cable on the seafloor with five primary nodes and three branching units for future expansion. The design includes six vertical profilers and two buoyed vertical profilers for water column studies. This infrastructure will provide unprecedented levels of power (kW/node) and real-time, high bandwidth (Gigabit/sec) two-way communication to sensors on the network to enable in-depth study and decadal time-series observations of globally significant ocean and Earth processes that are expressed regionally.

The following is a brief description of the five primary nodes being proposed through the OOI as part of Stage II of the RCO:

Node 1 (N1) Hydrate Ridge – Node 1 is located on the abyssal plain seaward of the central Cascadia deformation front along the Newport transect (Figs. 6 and 7). This transect serves a variety of interdisciplinary objectives, including studies of dynamic processes that control methane transport and hydrate formation, biogeochemical processes, geophysical studies of megathrust earthquake events and tsunamis, and regional and coastal water column studies. An extension cable with three sub-nodes is planned for the summit of Hydrate Ridge and the adjacent subduction zone forearc. The primary node will support a seismic/geodetic station and a water column mooring, as well as a 90-km-long extension cable that extends across the accretionary complex and up on to the shelf. This cable provides power and communications to several moorings of the West Coast Endurance Array at this site (see Fig. 3).

Figure 7 shows the location of the primary and secondary nodes along the eastern portion of the Newport Line. Gas hydrate related studies are primarily focused at secondary node NP1 on the southern summit of Hydrate Ridge (light purple shading). Subduction zone related objectives are addressed by instrumentation placed at each of the three proposed secondary nodes (NP1-NP3). Benthic studies, physical oceanographic, biogeochemical, and carbon flux studies will be addressed at a series of six moorings (five of which are part of the coastal PNW coastal observatory (blue stars)). The sixth mooring is a full water column vertical profiling

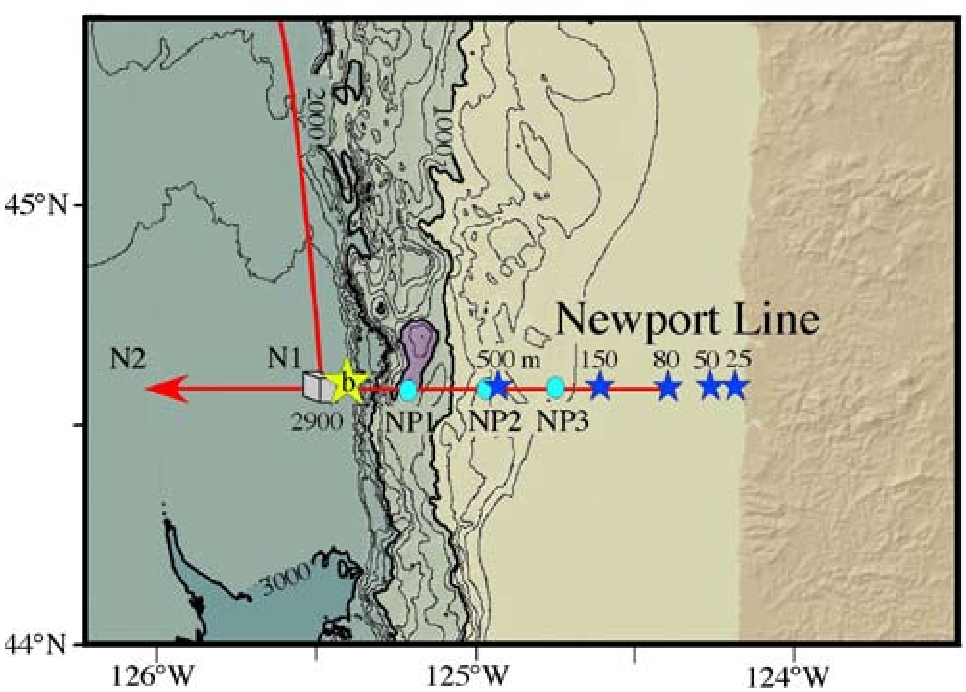


Figure 7. Map showing location of the primary and secondary nodes along the Newport Line. Gas hydrate related studies are primarily focused at secondary NP1 on the southern summit of Hydrate Ridge (light purple shading). Subduction zone related objectives are addressed by instrumentation placed at each of the three proposed secondary (NP1-NP3). Benthic studies, physical oceanographic, biogeochemical, and carbon flux studies will be addressed at a series of 6 moorings. Five of these are outlined in the coastal component of the CND (blue stars). The sixth mooring is a full water column vertical profiling mooring that will be placed on the backbone of the RCO (yellow star).

mooring that will be placed on the backbone of the RCO (yellow star). This node is also a key site for examining the coupling of pelagic particulate matter fluxes and benthic community processes across the shelf.

Node 2 (N2) Newport Line West – Node 2 is located in the interior of the Juan de Fuca plate at the western end of the Newport Line (Fig. 6). This node is critical for three types of regional scale studies: 1) it provides one of the few mid-plate sites for plate-scale seismology and geodynamics; 2) coupled with cabled profiling moorings at Node N1 and on the shelf along the Newport Line (through the coastal component of the OOI), the water column mooring proposed for Node N2 will enable studies of biophysical processes from the exceptionally productive upwelling zone over the shelf to the nutrient-poor, subtropical waters west of the shelf break; and 3) this node is key to studying the relationships between temporally-varying particulate fluxes and benthic community processes from slope to abyssal depths in real time. This transect of stations is important because it crosses the continental margin from the base of the slope (out of range of commercial fishing activity) and reaches the mid-plate.

Node 3 (N3) Blanco Fracture Zone – Node 3 is located along the active Blanco transform fault (Fig. 6). The Blanco node will be used for a seismic-geodetic experiment to understanding the basic physics of earthquake rupture by utilizing the short recurrence interval of magnitude 6-6.5 earthquakes on the Blanco transform fault to distinguish between the effects of geological heterogeneity and stress-state. This is also one of the sites identified for interdisciplinary water column studies that will link ocean dynamics, climate and ecosystem response. A network of secondary benthic nodes will cover a ~60 by 20 km wide area straddling the fault with a network of relatively low power instruments such as seismometers, strong motion sensors, fluid temperature probes, and geodetic transponders.

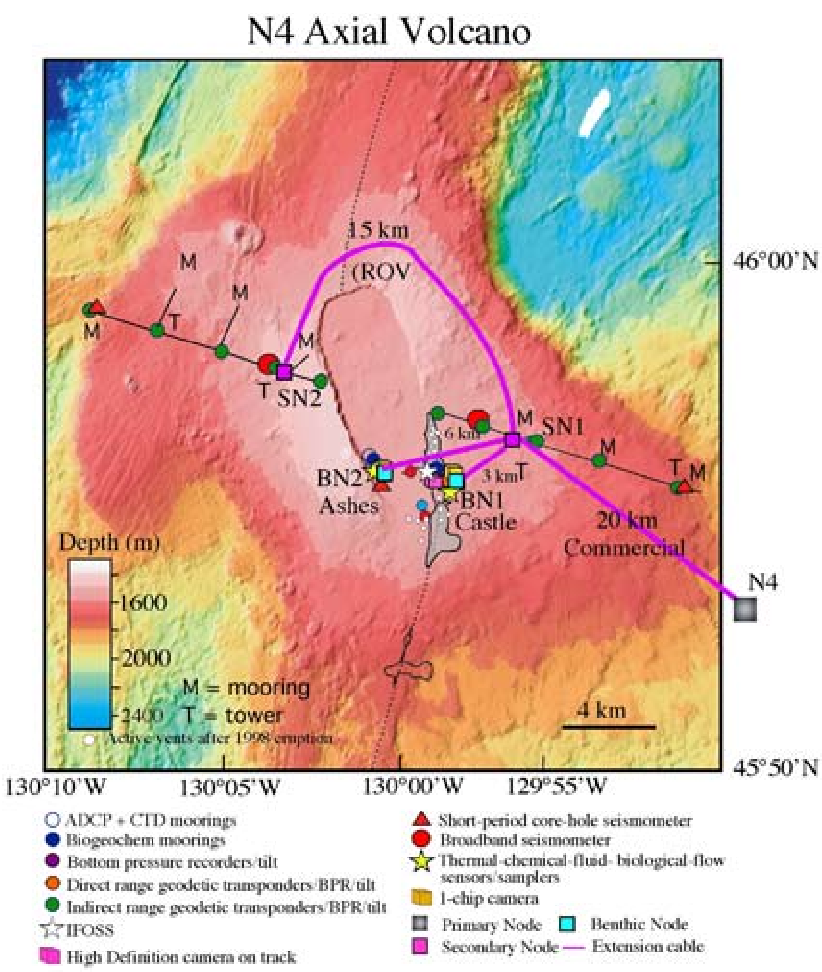


Figure 8. Axial Volcano is the largest volcano on the Juan de Fuca Ridge and hosts three robustly venting hydrothermal sites (Ashes, Castle, and Chasm (not shown)) within its summit caldera. NOAA has maintained a moored buoy observatory at this site for several years (NeMO). It has the longest co-registered time-series analyses of fluid and microbial community evolution following a volcanic eruption in the oceans. This area was the focus of five RFA's, and because of its importance in addressing the linkages among volcanism, crustal accretion, hydrothermal flow, and biological processes, extensive secondary infrastructure is planned for this site. Because this could be a hazardous environment, a 20 km extension cable is planned from the primary backbone cable. Multiple shorter cables will be laid with an ROV to provide power for an extensive array of sensors.

Node 4 (N4) Axial Seamount – Node 4 is located at the summit of Axial Seamount along the intermediate spreading Juan de Fuca Ridge (Figs. 6 and 8). Axial Seamount, which last erupted in 1998, has the most robust magma supply on the Juan de Fuca Ridge and is the site of the NOAA's New Millenium Observatory (NeMO; see http://www.pmel.noaa.gov/vents/nemo/). Given the work that has already been accomplished at this site, it presents an unparalleled opportunity for integrated long-term studies of active seafloor volcanism. It is also one of the sites identified for the deployment of a mooring that will be used for interdisciplinary water column studies that link ocean dynamics, climate and ecosystem response in the Northeast Pacific. The deployment of a vertical hydrophone mooring and a broadband seismometer at Cleft will maximize the area that will be covered by the hydroacoustic monitoring and plate scale seismology experiments. Two secondary nodes will be deployed on the western and eastern sides of the caldera at the summit of Axial Seamount (Fig. 8). A cable will extend from the eastern secondary node to a benthic node at the Castle vent site.

Node 6 (N6) Cascadia Subduction Zone – Node 6 is located seaward of the Cascadia deformation front and includes a cable with two sub-nodes to address subduction zone and water column objectives (Fig. 6). This transect is also co-located with a transect being planned as part of the PNW coastal observatory (see Fig. 3). The Cascadia Subduction zone is known to have generated historically enormous (Mw 9+) earthquakes and tsunamis. Recently reported correlations between forearc basin structure and the slip history of large earthquakes in other subduction zones provide a framework for designing a seismic and geodetic network that will lead to a better understanding of the subduction zone dynamics and earthquake/tsunami hazards in the Pacific Northwest.

OOI Global Observatory

Long-term continuous open-ocean observations are required for quantifying and understanding interannual-to-decadal changes in ocean circulation, water properties, water mass formation, and ecosystems, for observing episodic events and their impact, for providing reference sites for atmospheric time series

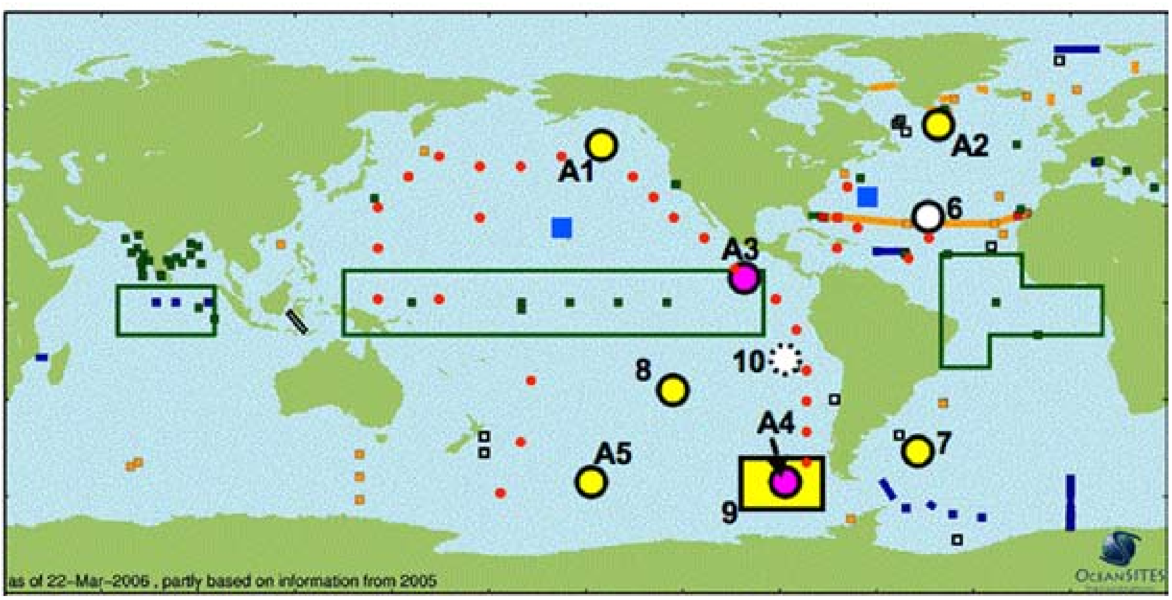


Figure 9. Distribution of OOI global observatory sites (large labeled filled circles and rectangle) relative to the OceanSITES near-term network and future DART buoy locations (red dots). The OOI sites labeled "A" have the highest but equal priority; the priorities of the remaining OOI sites indicated by numbers 6-10. Mooring types are indicated by color: yellow disks for acoustically-linked discus buoy, purple disks for SPAR buoy; and white disks for discus buoys with electrical-optical-mechanical (EOM) cables. The yellow rectangle shows one possible location for the relocatable Global Pioneer Array, which will consist of a backbone of four sub-surface moorings and four gliders. The existing long-term oceanographic time series sites at Hawaii and Bermuda, which are recommended for continued support through the ORION program (but no new OOI infrastructure), are shown by the blue rectangles. An acoustic source/receiver mooring tied to a separately-NSF-funded cabled junction box at HOT site ALOHA is also part of the CND.

and quantifying air-sea fluxes, for determining the role of the oceans in the global carbon cycle, for improving our understanding of the Earth's interior and geodynamics, and for measuring global plate motions and studying plate boundary processes. Moored buoy, open-ocean observatories are well suited to address these requirements, especially in remote ocean areas where cabled observatories are unavailable or prohibitively expensive to install. Moored buoy observatories are an important complement to other components of a global ocean observing system, like satellite remote sensing, profiling floats, surface drifters, gliders and research vessels.

Figure 9 shows the eight open-ocean, moored buoy observatories (labelled A1 through A5, and 6, 7, & 8) proposed for the global component of the OOI. The approach taken by ORION is to build a system that can address global science questions in truly novel ways and to contribute to a global network that by necessity will be international in scope. In Fig. 9 the OOI global sites are superimposed on a map from the international OceanSITES project which coordinates the international global ocean time series network, and is part of the Global Ocean Observing System (GOOS). This map also shows the locations of NOAA's Deep-ocean Assessment and Reporting of Tsunami (DART) buoys (red dots) in the Pacific and Atlantic. The OOI Global Observatory will be embedded in a larger network operated by NOAA and international partners, to which it will contribute new technology and occupy sites, especially in the Southern Ocean, from which observations are not currently available.

Three types of surface moorings will be used in the global observatory program: (1) an acoustically-linked discus buoy; (2) a discus buoy with a electro-optical-mechanical (EOM) cable linked to a seafloor junction box, and (3) a tri-moored spar buoy with an electro-optical (EO) cable to a seafloor junction box. The acoustically-linked system will be used in those cases where power does not need to be provided to sensors in the water column or on the seafloor. A key feature of this system is the ability to add or remove sensors from the observatory without recovery of the buoy or mooring, providing considerable flexibility in the operation and maintenance of sensor network. The EOM cable-linked buoys provide modest amounts of power (a few 10s of W) and two-way communication to a seafloor junction box and will be used, for example, with instrumented boreholes or where power needs to be provided to profiling moorings. The most advanced and technically challenging buoyed observatory envisioned for the OOI is the large tri-moored spar buoy. This system has been designed to deliver ~500W of power to a seafloor junction box and utilizes a C-Band satellite telemetry system to send ~500 Mbytes of data (or more) to shore each day. In comparison to the wave-following discus buoy, the spar design reduces the platform's motion in waves, especially heave and pitch motions, which are important for utilization of a high-bandwidth satellite telemetry system. The tri-moored design may also increase the survivability of the buoy, and the electro-optical cable connecting it to the seafloor, in very rough seas, as expected in the Southern Ocean.

In addition to fixed moorings at the eight sites shown in Fig. 9, the OOI CND includes plans for a relocatable array of moorings and gliders (a so-called global "Pioneer Array") that would temporarily enhance the single point, time series observations at one global site by providing greater spatial coverage and adaptive sampling capabilities. The relocatable array would consist of 4 subsurface moorings and several dockable AUV's. The initial deployment would be off southern Chile at global site A4 for a 2-3 year period (see yellow box in Fig. 9), but the location of subsequent deployments would be determined through peer-reviewed proposals. The CND also includes installation of a subsurface mooring with an acoustic source/receiver at the Hawaii Ocean Time-series (HOT) ALOHA site 100 km north of Oahu, Hawaii, to enable basin-scale acoustic thermometry using the other OOI global moorings in the North and South Pacific and to provide an acoustic network to track autonomous vehicles in the region. The CND does not recommend additional OOI infrastructure investments at the HOT/ALOHA or BATS sites. However, the importance of sustaining the long time series at these

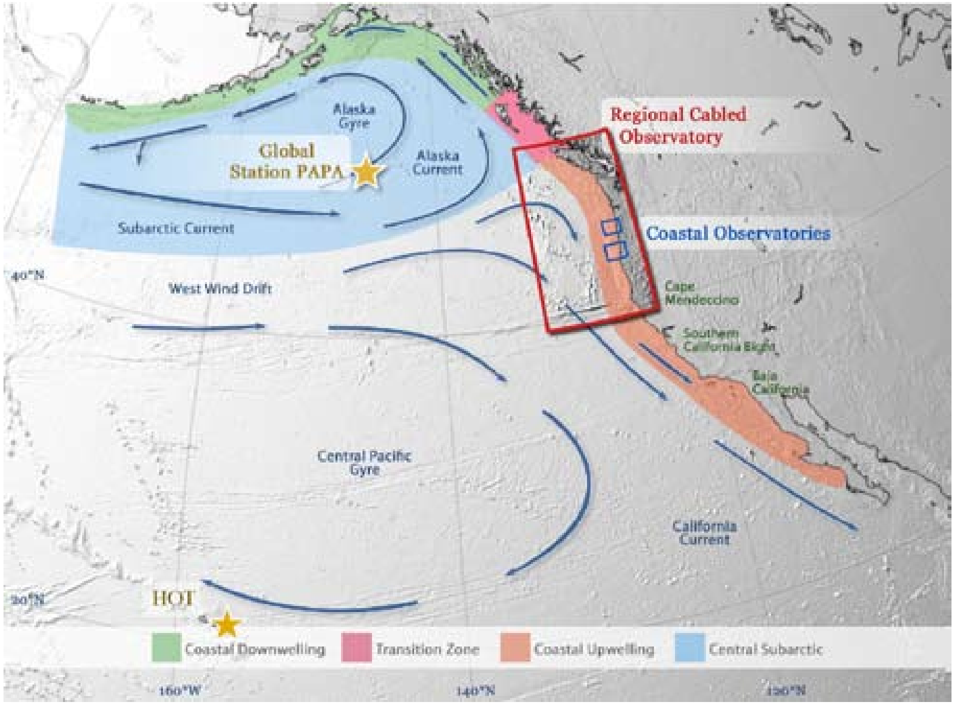


Figure 10. The Northeast Pacific is an example where opportunities exist to integrate results from of all three components of the OOI - global, regional, and coastal observatories. Station Papa (global site A1) is designed to study global circulation, biogeochemistry, and air-sea fluxes in the Northeast Pacific. It will thus provide a far-field reference point for the OOI-supported RCO (red box) and coastal Endurance arrays (two small blues) being installed off the coasts of Washington, Oregon and California.

sites for biogeochemical and oceanographic studies is widely recognized and the CND endorses continued support of time series studies at these sites.

The following is a brief summary of each global observatory site:

Site A1 - Gulf of Alaska, Station Papa
Nominal Site Location 50°N, 145°W.
Water Depth: 4,250 m
This northern site is characterized as a region of net CO_2 uptake with a productive ecosystem. It will provide an upstream physical and biological reference for the RCO and the West Coast coastal observatories (see Fig. 10), will extend long-term historical time-series obtained by ship occupation of the site and by occasional process mooring deployments, closes a gap in the global seismic network, will provide air-sea flux forcing information, and will exploit future synergy with a DART buoy in the vicinity.

Site A2 - Southeast Greenland
Nominal Site Location: 60°N, 39°W.
Water Depth: 2,800 m
This site is a high-latitude location in the North Atlantic, in a strong total and anthropogenic CO_2 uptake region coupled with water mass formation, which is a productive ecosystem and fisheries regime responding strongly to climate variations, and it provides a site to study air-sea flux forcing in an extreme and until now unobservable environment. Real-time access and control of the simultaneous multidisciplinary observations will permit investigations of the forcing of processes leading to climate-related changes in the ecosystem, CO_2 dynamics, and water mass formation.

Site A3 - RIDGE, East Pacific Rise
Nominal Site Location: 9° 50' N, 104°17' W;
Water Depth: 2,500 m
Transient geological processes such as hydrothermal cracking, tectonic earthquakes, and seafloor eruptions will be detected by a local array of seafloor seismographs and geodetic sensors at this RIDGE 2000 Integrated Studies Site. Optical, chemical, and biological sensors and analyzers will be used to examine the temporal and spatial responses of the hydrothermal system to these transient perturbations. The hydrothermal system will be monitored using a diverse suite of instrumentation receiving power from a source on a buoy and having a wired telemetry link to the buoy. Cabled instrumentation will be distributed over an area 11 km x 9 km. Real-time monitoring and instrument command will allow the sampling strategy of in-situ and AUV-mounted instrumentation to be adapted appropriately.

<u>Site A4 - Southern Ocean, Southwest of Chile</u>
Nominal Site Location: 55°S, 90°W.
Water Depth: ~4,800 m

This Southern Ocean site received the highest overall interest as a truly transformative observatory location. It is an important water mass formation site (AAIW), a strong localized southern CO_2 uptake region (Fig. 11), is a productive ecosystem regime, has virtually unobserved processes, closes a gap in the global seismic network, and will provide critical Southern Ocean air-sea flux forcing information. Real-time access and control of the simultaneous multidisciplinary observations will permit the investigation of the forcing of processes leading to climate-related changes in the Southern Ocean.

<u>Site A5 - Southern Ocean, Pacific-Antarctic Ridge</u>
Nominal Site Location: 55°S 150°W.
Water Depth: ~3,500 m (nominal)

This site is a Southern Ocean equivalent in some aspects to station PAPA in the north Pacific. It is a high-latitude location, in a southern CO_2 uptake region (Fig. 11), a productive ecosystem regime, has virtually unobserved processes, closes a gap in the global seismic network, provides critical southern ocean air-sea flux forcing information.

<u>Site 6 - DSDP Hole 396B, Mid-Atlantic Ridge</u>
Nominal Site Location: 22°59.142'N, 43°30.900' W.
Water Depth: 4,459 m

This site is located at Deep Sea Drilling Project (DSDP) Hole 396 B on 13 Ma crust immediately west of the Mid-Atlantic Ridge. Hole 396 B is equipped with a re-entry cone, and has a total penetration of 406 m, of which 255 m is in basement. The equatorial Atlantic, located 145°-170° from the Western Pacific subduction zones, is the optimum region to observe seismic waves that sample the outer core and core-mantle boundary. A broadband borehole seismic station at this site will record these phases; allow measurement of the anisotropy structure and spectrum of lateral heterogeneity of the oceanic upper mantle; and provide long-term observations of earthquake rupture along a large oceanic transform fault. Seismic measurements will be augmented by seafloor electromagnetic and

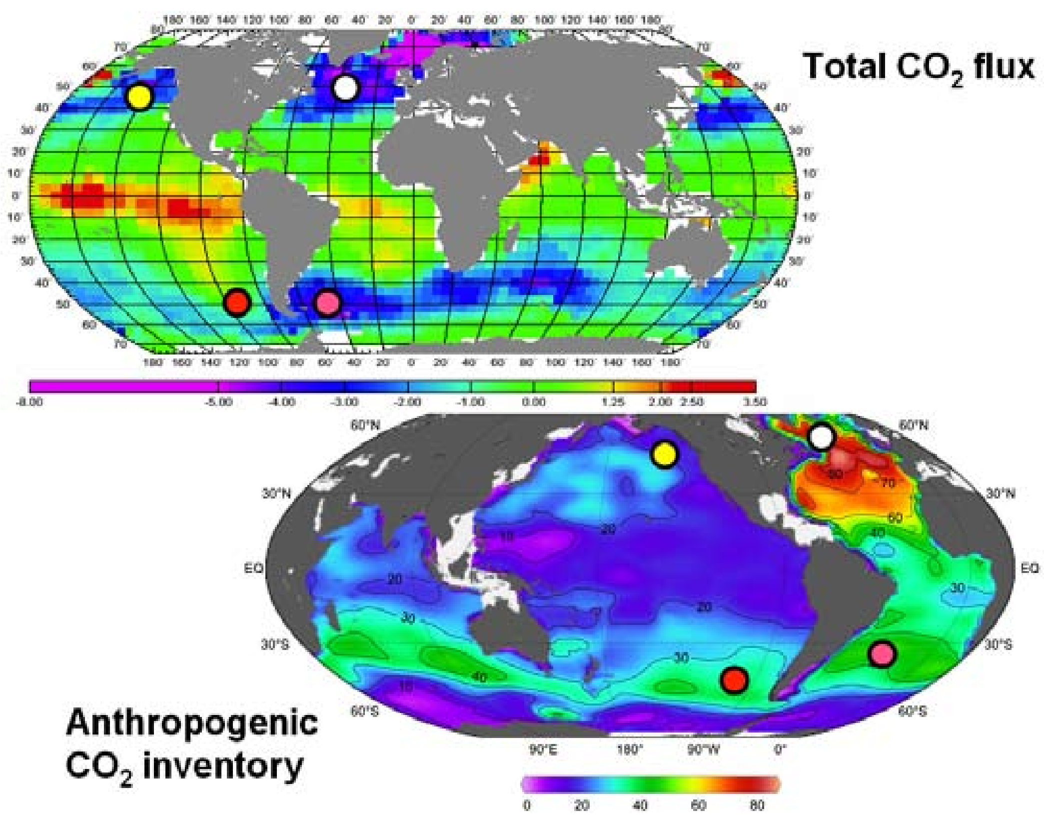


Figure 11. Recommended high-latitude global sites (circles) in regions with large CO2 uptake or inventory without present long-term observing capability.

magnetic field measurements. This site will also allow study of the effects of Saharan dust input to this region of low primary productivity.

<u>Site 7 - Argentine Basin, South Atlantic</u>
Nominal Site Location: 42°S, 42°W.
Water Depth: 5,200 m
This high-latitude site in the South Atlantic is in a region of large CO_2 uptake (Fig. 11), high primary productivity, and strong vertical variation of ocean dynamics. The site closes a gap in the global seismic network, and will provide critical Southern Ocean air-sea flux forcing information.

<u>Site 8 - South Pacific Subtropical Gyre</u>
Nominal Site Location: 28°S, 120°W.
Water Depth: 3,400 m
This site, like Site 6, is located in a region of low primary productivity, and hence contrasts with sites A1, A2, and 7. The site is an important node for the acoustic tomography network.

4. Representative Science Questions and their Links to the OOI CND

This section describes how the infrastructure described in the OOI CND, and summarized in Section 3, will be used to address four specific science questions. These questions, which fall within the broad scientific themes outlined in the OOI Science Plan, are presented only as examples to illustrate the diversity of important scientific investigations the OOI infrastructure will facilitate. We do not mean to imply that these are the only scientific questions the ORION Program will address or that that these are even the highest priority questions. The observations and experiments conducted by the ORION Program at these sites will be chosen based on an NSF-run, peer-review process and will encompass the broad range of ocean and Earth science.

What is the ocean's role in storing anthropogenic carbon and controlling future atmospheric CO_2 levels?

A fundamental and urgent scientific question that requires sustained ocean observations is determining the ocean's role in storing anthropogenic carbon and thus its effect in mitigating future increases in atmospheric CO_2 levels. Ocean waters contain greater than 50-fold more CO_2 than the atmosphere, and hydrate deposits in continental margin sediments contain more than twice the hydrocarbon carbon of all known fossil fuel reserves. Thus, small perturbations in ocean and sediment carbon cycling potentially can result in substantial changes to atmospheric concentrations. Since the Industrial Revolution, atmospheric CO_2 levels have risen from pre-industrial, interglacial values of 280 ppm to approximately 385 ppm today. This increase represents approximately half of the total estimated anthropogenically released CO_2, with the oceans adsorbing most of the other half.

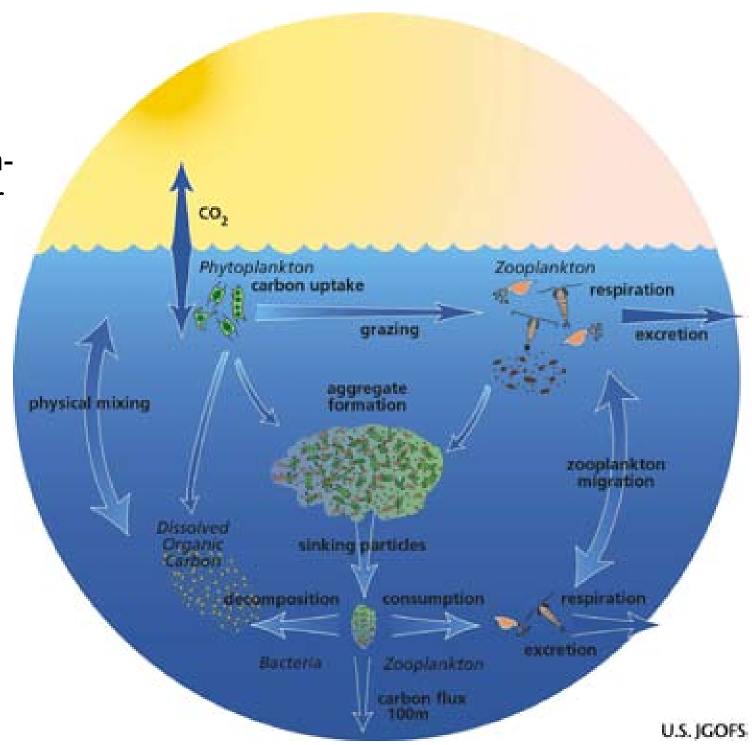


Figure 12. Schematic drawing of the "biological pump" – a set of biological processes that convert dissolved CO_2 in surface waters into particulate and dissolved organic C; some of which sinks or is otherwise moved to deep ocean waters. Some of the C removed from surface waters can be replaced by CO_2 that exchanges between the atmosphere and the ocean. Thus, the net effect of these processes is to "pump" CO_2 from the atmosphere to the deep ocean.

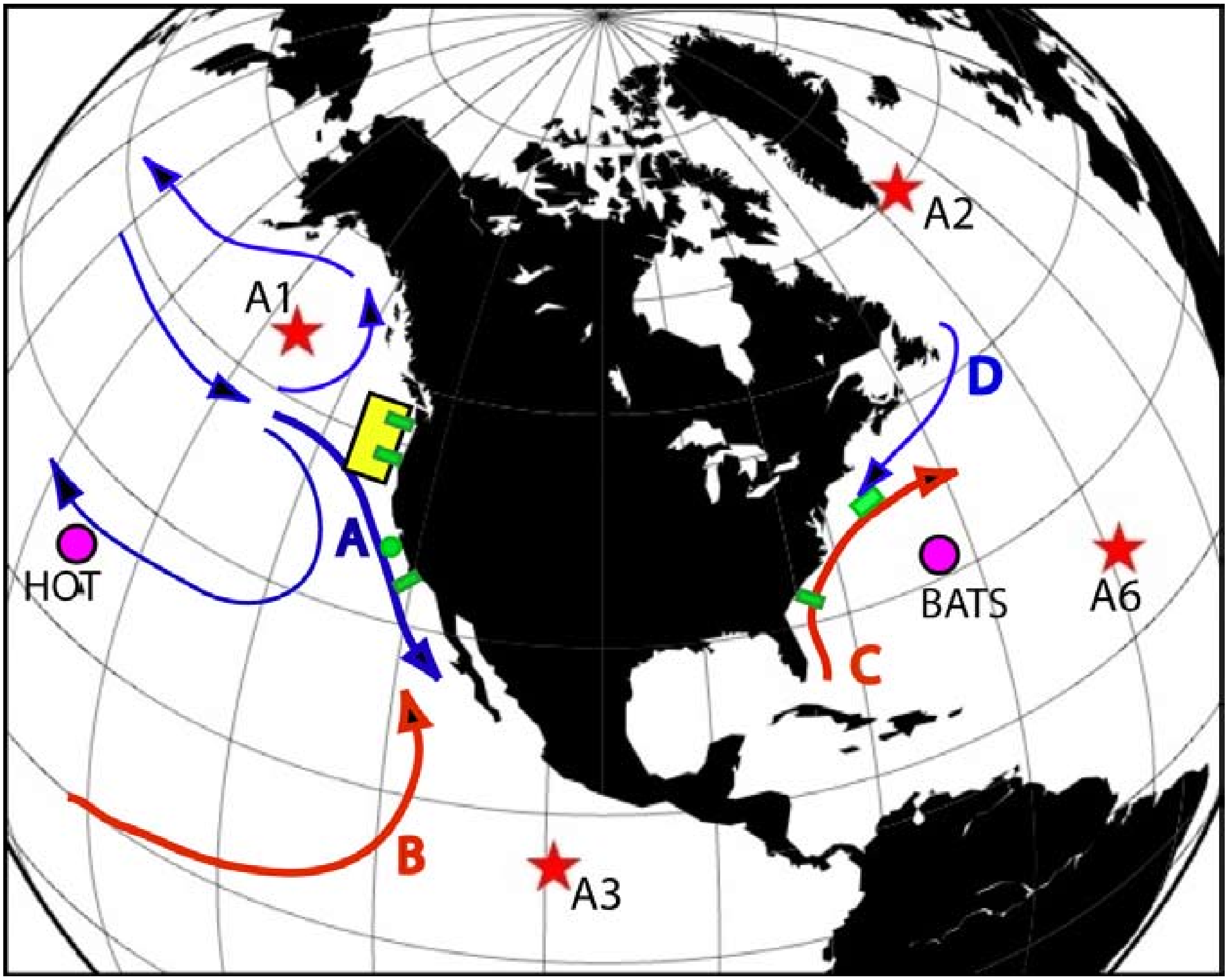


Figure 13. All components of the OOI (global, regional, coastal) will be required to understand the complex interactions of changes in ocean circulation, ecosystems and climate on the North American coastal ocean. The RCO (yellow box) and West Coast coastal observatory (green boxes) will be installed on a narrow continental shelf, bounded by an southward flowing eastern boundary current (California Current, labeled "A"). Wind-driven coastal upwelling in this region supports high rates of primary production. In contrast, the East Coast, where the SAB Endurance Array and Pioneer Array off southern New England will be located (green boxes), is associated with a broad, shallow continental shelf and a western boundary current (Gulf Stream, labeled "C"). Winter storm and wind patterns in the North Pacific change on a 30-50 year cycle (Pacific Decadal Oscillation). These effects are measurable at Station Papa (global site A1; red star) and also in the nutrient content and other properties of the water masses that will move south through the RCO and along the West Coast. The ENSO cycle has effects that propagate from south to north ("B") along the west coast. During large El Nino events (e.g.1997-98) adverse effects of warm, nutrient-poor waters that move north along the coast adversely impact ecosystems and fisheries as far north as the RCO. The ENSO cycle also affects rainfall patterns and river runoff on the U.S. East Coast affecting coastal waters, for example, in the SAB. Off the East Coast, the Gulf Stream is the primary source of nutrients for the SAB and for the slope waters north of Cape Hatteras. The strength of the Labrador Current ("D") differs from year-to-year, apparently associated with the state of the NAO. It is a source of cold, low salinity waters that move south along the northeast coast, into the Gulf of Maine and the slope waters. During years of strong flow, it pushes the north wall of the Gulf Stream more than 100-km south. Ecosystem productivity is lower during years of strong flow apparently owing to the lower nutrient content of waters that originate from the north.

The exchange of CO_2 between the atmosphere and the oceans and its fate are mediated by two phenomena. The "solubility pump" is controlled by CO_2 solubility in seawater and gas exchange rate between the atmosphere and the ocean, which principally depend upon water temperature and wind speed, respectively. Net storage of anthropogenic CO_2 is, in turn, controlled by ocean transport away from the sea surface. The second mechanism important to the fate of CO_2 in the ocean is the "biological pump" (Fig. 12). Biological productivity produces particulate and dissolved organic carbon in the surface photic zone. Those materials not recycled within the food web are ultimately transported to deep waters and ocean sediments where they are not exchanged with the atmosphere for centuries to millennia due to the long residence time (thousands of years) of deep ocean waters. Higher CO_2 concentrations in deep ocean waters, compared to surface waters concentrations, is the long-term result of the biological pump.

The OOI CND targets a variety of the critical research needs to understand the ocean carbon cycle. The planned distribution of the global observatory buoys emphasizes high latitude regions that are critical areas for anthropogenic CO_2 uptake and deep water transfer (Fig. 9). Owing to the harsh conditions, especially during winter seasons, there are few existing and no sustained ship-based gas exchange observations at these locations. Thus, gas exchange measurements are planned for site A4 and A5 in the Southern Ocean and at sites A1 and A2 in the North Pacific and Atlantic, respectively, to provide year-round observations at high latitudes not currently available by any other means.

The OOI coastal observatory will enable several critical aspects of carbon cycle dynamics and terrestrial-coastal-open ocean C exchange to be studied. The relocatable coastal Pioneer observatory array, for example, is designed specifically to integrate fixed and mobile platforms to ensure that the measurement resolution needed to define specific mixing and exchange processes is obtained. Although this array is intended to be relocatable with deployment locations and scientific focus competed within the research community, the initial, 5-year deployment is envisioned to be on the Mid-Atlantic Bight shelfbreak off southern New England. The goal of this experiment is to examine cross-margin exchange processes at the shelfbreak, which is at the interface between the broad continental shelf and adjacent slope that is influenced by the Gulf Stream further offshore. Quantifying mass and chemical exchanges at the shelf break is fundamental to advancing understanding coastal-open ocean C exchanges.

The long-term coastal Endurance arrays OOI will establish in the South Atlantic Bight (SAB) off Georgia and off the coasts of Washington, Oregon and California (Figs. 3 and 4) are well situated for studies related to the role of the ocean margins in the ocean carbon cycle. These locations represent major, and contrasting, types of coastal systems, both in the U.S. and globally (Fig. 13). The West Coast Endurance Array will be installed on a narrow continental shelf, bounded by an equatorward flowing eastern boundary current system. Wind-driven coastal upwelling in this region support high rates of primary production, and the coupled biological and physical dynamics are representative of the eastern coastal systems of the Pacific from Vancouver Island to central Chile, and the eastern coast of the Atlantic from the Iberian Coast to Cape Town (Chen et al., 2003). Compilations suggest that these types of systems provide ~40% of the particulate organic carbon transported to below the main thermocline. The other general category of continental margin environment is the "recycling" system (Chen et al. 2003) of which the SAB is representative. These systems are those with wide, generally shallow, sandy continental shelves and a relatively long water residence time. On the U.S. East Coast this system is bounded by the Gulf Stream, a major poleward flowing western boundary current. This type of shelf environment is thought to recycle rather than export most organic matter produced.

Recent studies of the upwelling system off the West Coast of North America indicate an important set of processes of potential significance to the net flux of CO_2 from the atmosphere to the ocean, but which are not yet well understood (Hales et al., 2005). In particular, under circumstances in which plankton production in upwelling waters consumes all of the nutrients in the upwelling water, including the preformed nutrients (thus depleting CO_2 content to the concentrations at or below levels at the time the water mass was formed), there is a potential for a net flux of CO_2 from the atmosphere to the ocean. For this to be a significant process, however, the net flux of CO_2 has to occur before the upwelled waters sink beneath the thermocline or are warmed to the extent that CO_2 begins to flux back to the atmosphere. Measurements along the West Coast Endurance Array of PCO_2, heat flux, phytoplankton biomass, phytoplankton productivity, and nutrient concentrations at fixed depths or measured continuously from vertically profiling platforms could resolve the question of whether plankton production in upwelling waters occurs at sufficiently fast rates to consume preformed nutrients. Ocean current and water density measurements at the fixed sites on the West Coast, supported by measurements from satellites and from mobile assets such as gliders, can be used to determine the residence time and fate of upwelled water masses. Integration of these measurements will resolve questions related to the net flux of CO_2 between the atmosphere and upwelling waters and how the rates of these processes change under different ocean climate conditions (e.g. different stages of ENSO) or with latitude along the west coast of North America. All the sensors needed to make these measurements are available and results can be expected early in the ORION program.

While the U.S. East Coast, represented by a broad shelf and western boundary current, is thought to recycle rather than export most organic matter produced, these types of shelf systems may impact the ocean carbon cycle in other ways. Extensive salt marshes and other terrestrial vegetation that line the coast contribute significant organic and inorganic carbon to nearshore waters that are efficiently transported to the shelf via tidal exchange (Ducklow and McCallister. 2004). With this added C source, the shelf can export C to both the atmosphere and adjacent ocean waters. In the SAB and in other similar regions, the traditional strategy of estimating net ocean CO_2 uptake solely by air-sea exchange is invalid. Detailed studies of the relative dynamics of the rates and controls on lateral transport versus air-sea exchange are needed. Additionally, during the winter, the shallow shelf waters are cooled to temperatures well below the adjacent Gulf Stream. At present, it is unknown to what extent shelf waters containing comparatively high concentrations of C cascade over the shelf break and sink below the less dense Gulf Stream, although recent estimates indicate that this is potentially an important process (Ivanov et al. 2004).

The combination of seafloor measurements of current and pressure under the Gulf Stream using inverted echosounders, HF radar measurements of surface currents across the shelf and Gulf Stream, and detailed measurements planned at the cross-shelf observatory nodes will greatly advance understanding of the interplay between the Gulf Stream dynamics and shelf exchange which is critical to assessing these potential C transfers (Fig. 4). The SAB tower station couplets R7/R8, R2/R3 and R4/R5 could be instrumented with sensors to measure gradients of important C system constituents across the mid to outer shelf. Sensors to measure PCO_2, organic particles and dissolved organic matter (or at least that portion of dissolved organic matter that strongly absorbs at near-UV wavelengths) are currently available. Any or all of the towers could be instrumented for air-sea exchange experiments including direct measurements of the CO_2 flux, as well as the flux of sensible and latent heat. Towers near the shelfbreak at locations R8, R3 and R4 could provide direct measurements of the C system parameters mentioned above, as well as measurements of T and S to calculate water density. These direct measurements, coupled with heat flux calculations, could then be used to calculate the potential for shelf waters to sink during the colder months of the year and to what depth. Thus, an accurate calculation of the seasonal C flux from shelf to sub-thermocline ocean waters based on direct measurements will be possible.

What is the impact of storms and other extreme events on exchanges of heat, gases and nutrients within the ocean-atmosphere-Earth system?

The large surface area and volume of the world's oceans, the high heat capacity of sea water, its chemistry and marine life, and the ocean's ability to

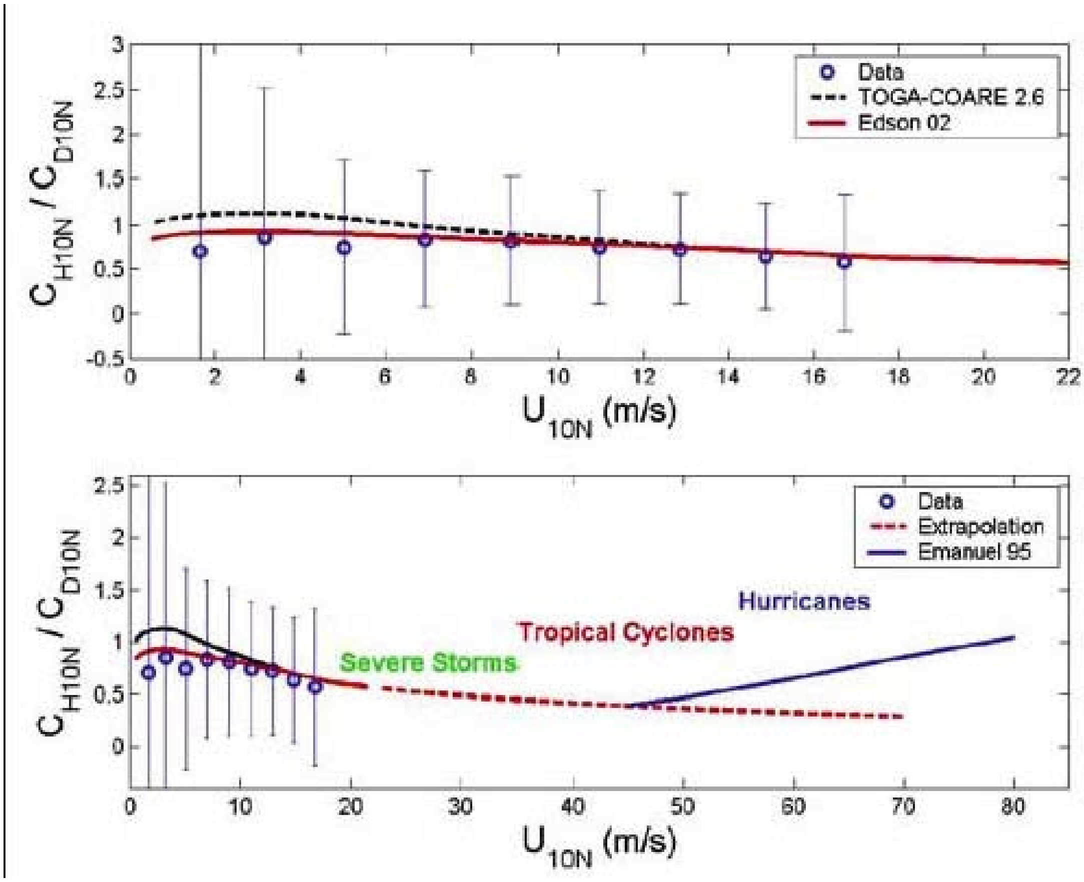


Figure 14. Relationship between the ratio of heat to momentum exchange coefficients (y-axis) versus wind speed (x-axis). Points show where measurements have been made; lines represent extrapolations made for models by Emanuel (1995) and Edson (2002). Note how few data exist for extreme storm events (>20 m/s or ~45 mph).

transport properties across a wide range of latitudes make the oceans a key component of the coupled ocean-atmosphere-land system. For example, the interaction between the sea and the atmosphere strongly influences the development and intensification of storms, including tropical storms and hurricanes, and controls our changing weather on time scales of days to centuries. Wind-induced turbulent mixing in the uppermost ocean affects planktonic community structure, the exchange of nutrients between the mixed layer and deeper ocean, and cycles of primary productivity in the upper ocean. The exchange of heat and gases between the ocean and atmosphere also play a critical role in longer-term changes in the global climate. An accurate quantification of the exchanges of mass, heat, momentum, and chemical constituents between the ocean and atmosphere is essential for a better understanding of these processes.

In the last few decades, substantial progress has been made in making direct measurements of air-sea momentum, mass and heat exchange from buoy, research vessels and other moving platforms (Anctil et al, 1994; Edson et al., 1998; Fredericksson and Davidson, 2003). These measurements have been used to develop the latest generation of flux parameterizations, which agree well with established drag and transfer coefficients for wind speeds between 5 and 18 m s^{-1} (Fig. 14; top panel). However, decades of measurements from research vessels have done little to advance our understanding of air-sea exchanges in severe storms at wind speeds above 20 m s^{-1} (~45 mph) or in tropical storms or hurricanes (Fig. 14; bottom panel). This lack of data at higher wind speeds is a major impediment to forecasting storm intensity accurately. For example, numerical modelers have shown that extrapolation of current parameterizations (broken red line in Fig. 14) does not explain hurricane formation due to too much drag and/or too little heat exchange between the ocean and atmosphere (Emanuel, 1995; Edson, 2002). Hurricane modelers have proposed a different parameterization (blue line in Fig. 14), but it is untested by direct observations.

Our inability to make measurements at high wind speeds is due to the harsh conditions encountered

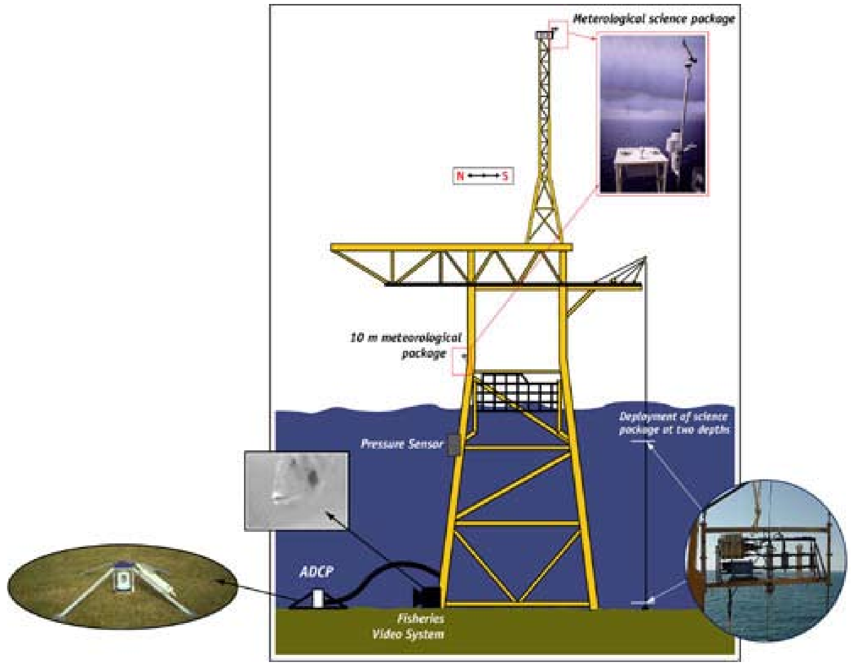


Figure 15. One of eight towers that are part of the South Atlantic Bight Offshore Observation Network (SABSOON) that are being instrumented to provide measurements of shelf meteorology, circulation, hydrography and bio-optical variability with continuous real-time data telemetry to shore. OOI plans to link its South Atlantic Bight Endurance Array to the SABSOON observational network (Fig. 4) providing unprecedented, simultaneous measurements of the importance of episodic events, such as severe storms and hurricanes, on vertical fluxes across the air-sea boundary, through the water column, and at and across the benthic boundary.

at sea during storms and concerns for the safety of the vessels and those aboard. High sea states and surface winds, low visibility and corrosive sea spray often make aircraft operations near the sea surface too dangerous to conduct during intense storms. For example, a recently completed component of the Office of Naval Research's Couple Boundary Layers and Air-Sea Transfer (CBLAST) used aircraft and air-deployed sensors to investigate air-sea exchange in hurricane conditions. The aircraft component of this program successfully measured fluxes near the ocean surface in wind conditions that exceeded 30 m s^{-1} (Black et al., 2006). However, damage to one of the engines due to ingestion of sea-spray forced operations to higher altitudes during the latter phases of the experiment.

Aircraft and ship-based operation will continue to play an important role in air-sea interaction investigations. This is particularly true for the latest generation of oceanic profiler that can be air-dropped into the ocean in advance of severe storms. However, a number of the meteorological and upper ocean components of the OOI will take a significantly different observational approach to overcome current operational limitations in studying severe storms. Specifically, some OOI infrastructure will be placed in regions of the world's oceans that routinely experience severe weather such as "hurricane alley" southeast of Cape Hatteras in the SAB, in the Southern Ocean, and high latitudes in the North Pacific and Atlantic. The high bandwidth, two-way communication and power afforded by these platforms (compared to traditional moorings) will allow the deployment of sophisticated instrumentation that can be run continuously or be activated whenever necessary by command from shore. In particular, the OOI will make a unique contribution to investigations of severe storms by establishing sites in both the coastal and open ocean where long-term, continuous, direct measurements of momentum, heat and mass (e.g., water vapor and CO_2) fluxes can be made and by promoting the development of new generations of sonic anemometers, hygrometers and thermometers that can operate in high wind speed and spray conditions. These measurements will be combined with the oceanographic measurements at all sites to improve our understanding of air-sea exchange and oceanographic forcing/response at all wind conditions.

All surface expression moorings deployed by OOI will be equipped with a standard suite of sensors for air-sea interaction measurements, providing data from both the coastal and open ocean. Of particular interest, however, will be the surface moorings and instrumented SABSOON towers along the South Atlantic Bight (SAB) coastal Endurance Line (Figs. 4 and 15). A variety of atmospheric processes affect the SAB shelf. Winter cyclones that impact the U.S.

East Coast can develop in or cross this region, and tropical storms and hurricanes can pass through the SAB in summer and early fall. Interestingly, maximum wind speeds observed at the SABSOON towers to date have been associated with the passages of squall lines and thunderstorms. These extreme wind events were associated with rapid decreases in air temperature, downpours, and 6-minute-averaged wind speeds of >40 m s^{-1} (89 mph). The fully instrumented SABSOON tower network combined with information from the SAB Endurance Line will provide a unique observational opportunity for spatial coverage below and above the water surface over the duration of extreme storm events. For example, the towers are capable of supporting upward looking remote sensing devices and automated raw insonde systems to provide continuous measurements of boundary layer winds, temperature, humidity, and cloud base height for extensive periods. As such, the ability to conduct in-depth investigations of coupled ocean-atmosphere processes in the SAB region provides an ideal location to develop and improve coupled air-sea models for marine forecasts of wind, waves and currents.

Our poor understanding of air-sea fluxes during winter at high latitudes, especially in the remote Southern Ocean, also limits our ability to quantify these fluxes on a global scale. The OOI will make a unique contribution to improving global estimates of air-sea fluxes by establishing the first permanent instrumented mooring in the remote Southern Ocean (e.g., sites A4 and A5, Fig. 9). Additionally, the West Coast Endurance Array (Fig. 3) will provide ample opportunities to investigate the impact of mid-latitude cyclones upon the Northeast Pacific. These are areas of persistent high winds and storms, which will be ideal for studies of air-sea fluxes under these conditions. This is particularly true of the exchange of CO_2 between the ocean and atmosphere at mid to high latitudes where CO_2 exchange may be significantly enhanced by whitecapping (e.g., Wanninkhof and McGillis, 1999; McGillis et al., 2001). The mid to high latitudes represents the primary oceanic sink of atmospheric CO_2 over the global ocean. Therefore, an accurate parameterization of the CO_2 flux in these regions is of critical importance for accurate estimates of the global carbon budget, climate model forecasts, and ultimately predictions of climate change.

What is the planetary significance and evolutionary importance of microbial activity in the ocean and in the newly discovered sub-seafloor biosphere?

The oceans cover ~70% of the planet and the most abundant forms of life in the oceans are the marine microbes - the bacteria, archeae and protozoa. These microscopic organisms are the principal engines that drive biogeochemical cycling of major elements such as carbon, nitrogen, phosphate, and sulfur. For example, about 50% of organic carbon production on Earth occurs within the ocean and the vast majority of this organic carbon is generated and remineralized by marine microbes. Microbial processes also control all sulfur reduction/oxidation, nitrogen fixation, ammonia oxidation and denitrification that occurs within the oceans. Microbes additionally serve as important “reporters” for physical-chemical changes in the marine environment as their growth is closely coupled to environmental conditions. Identifying the community of microorganisms present in an ecosystem and how the composition of this community changes over time is a critical first step for understanding ecosystem function and for predicting how ecosystems will respond to changes in environmental conditions from either shorter-term (e.g., eutrophication of coastal waters, over-fishing) or longer-term perturbations (e.g., global climate change).

Current notions of the oceanic food web and the carbon and energy cycles of marine ecosystems are rapidly evolving due to ongoing discoveries of new and diverse groups of marine microbes and microbial capabilities. These new discoveries are occurring despite the fact that relatively few marine microbes can be isolated and cultivated in the laboratory. The marine cyanobacterium *Prochlorococcus* is now known to be the most abundant photosynthetic organism in the open ocean (Fig. 16). Archaea with unknown community functions were recently discovered to numerically dominate deep-sea planktonic communities. Newly discovered marine microbial capabilities include novel light-dependent pathways in pelagic marine bacteria (Béjà et al, 2000; Kolber et al., 2001) and nitrate-reducing methanotrophy in marine sediments. Many of the most recent discoveries about microbes have been derived from new DNA-based approaches, the most spectacular example of which is the environmental DNA sequencing of the Sargasso Sea where millions of genes were identified in a single experiment (Venter et al., 2004). These discoveries are exciting, but incomplete; the diversity, functional complexity, vertical distributions and temporal variability of marine microbial communities remain largely unknown.

Even less is known about microbial processes in sub-seafloor environments. Microbial cells in sub-seafloor sediments constitute a large fraction of Earth's total biomass. Tantalizing features, in the form of mineral-weathering textures, provide evidence of microbes in the basaltic crust below the sediment. The greatest depth of life beneath the seafloor, the impact of sub-seafloor microbes on global biogeochemical cycles, the linkages between geological, biological and chemical processes, and the extent to which sub-seafloor life is fueled by geologic processes (mineral weathering, mineral-catalyzed hydrocarbon formation, radiolysis), are unknown. Community connections between oceanic microbes and sub-seafloor microbes are also unknown. The roles of oceanographic processes (e.g., tides, ocean circulation), geologic processes (e.g., crustal deformation, sediment compaction), and combined processes (e.g., heat transport) in driving sub-seafloor fluid movement are little explored. All of these processes must be monitored at relatively fine timescales (hours to weeks) for long intervals of time (years to decades); this need is particularly acute for the geologic processes, which are often expressed episodically and unpredictably (e.g., as earthquakes and volcanic eruptions). The roles played by those processes in formation of sub-seafloor communities and in microbial exchange between oceanic and sub-seafloor communities are completely unexplored.

Water column: The marine realm has been and continues to be dramatically impacted by human activities. It remains exceedingly complicated, however, to assess the current impacts (let alone predict future impacts) of these physical and chemical changes on marine food webs. For example, there is a growing sense that outbreaks of harmful blooms of toxic algae are occurring more frequently, are lasting longer, and are spreading to more places (Fig. 1). In addition, the average pH of the surface ocean has decreased significantly due to the burning of fossil fuels. All organisms that precipitate calcium carbonate to form their shells will ultimately be affected by lower pH ocean waters (Orr et al., 2005). These organisms include corals (with their incredibly diverse microbial communities), coccolithophorids (phytoplankton), and many planktonic snail-like organisms that serve as important food sources for fish. Are the increase in harmful blooms a reflection of disrupted ecosystems as many suggest? How will removal of a major group of microbes such as the coccolithophorids ripple through the food web?

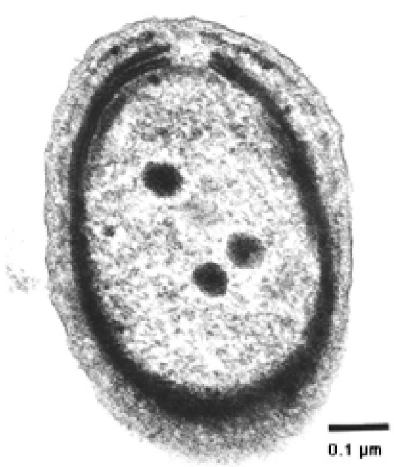


Figure 16. The marine cyanobacterium Prochlorococcus, discovered only in the last 2 decades, is now known to be the most abundant photosynthetic cell in the oceans, often reaching 105 cells ml-1 and accounting for a significant fraction of the chlorophyll in the oceans. The cells are less than 1 micron in diameter, and are quite unusual for prokaryotes in that they contain divinyl chlorophyll a and b as their primary light-harvesting pigments.

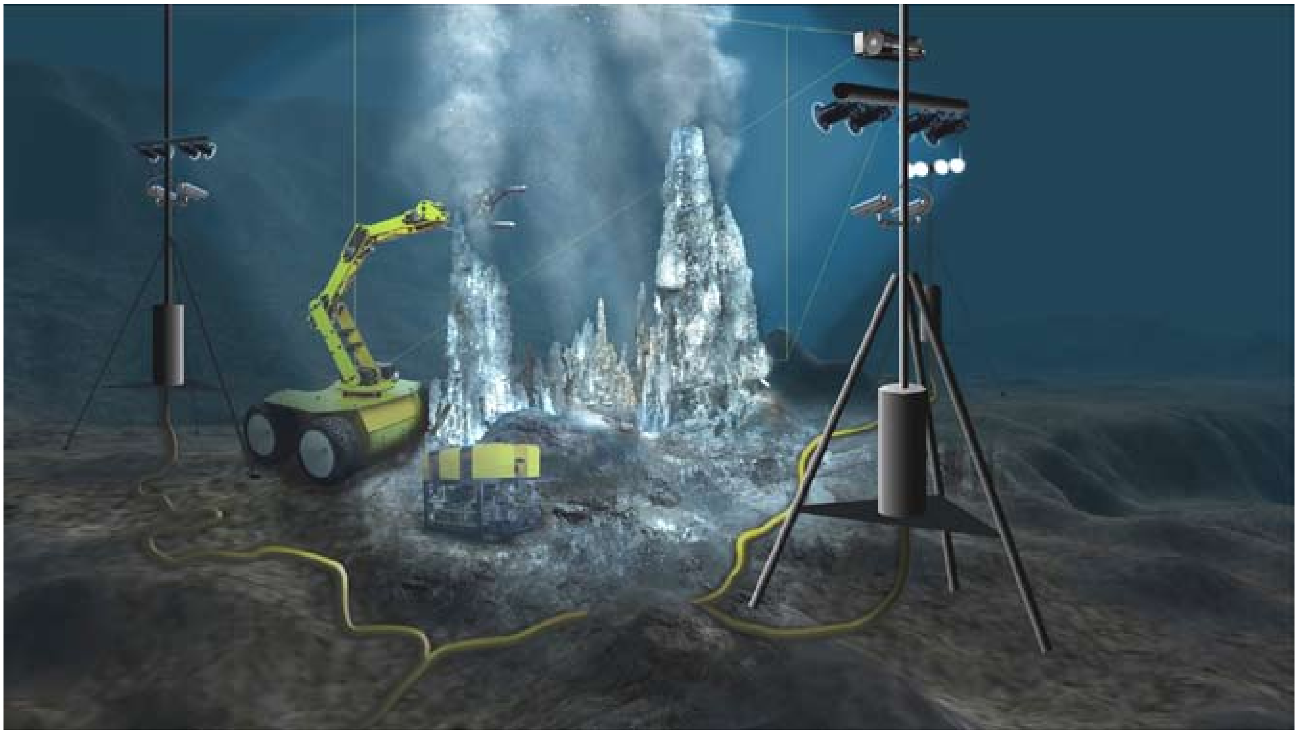


Figure 17. RCO Nodes N4 (Axial Seamount) and N7 (Endeavour Segment) and global site A3 (East Pacific Rise) will provide the power and bandwidth to study microbial activity in the presence of active submarine volcanic systems. One of the most exciting prospects in this field of research is that sophisticated seafloor observatories incorporating in situ seafloor laboratories, like that shown here, or instrumented drill holes, will provide microscopic and molecular analyses of microbial communities, quantitative analyses of fluid chemistry and continuous measurements of temperature, pressure, and fluid flow that will place new constraints on the nature and extent of life in extreme environments on Earth.

Microbes impact ocean processes on timescales ranging from seconds/hours/days to decades/millennia and on spatial scales that range from microns to kilometers. Ship-based sampling strategies simply cannot capture these different time and spatial scales nor the complexity of the microbial communities. Long-term, continuous observations associated with ocean observatories will provide information within the hourly to yearly window of time and on spatial scales that will average over hundreds of kilometers, depending on the complexity of the array. The ability to collect biological/chemical/physical data over long time series will ultimately provide insights into the resiliency/stability of marine ecosystems.

Sub-seafloor: Study of sub-seafloor life requires ocean observatories for at least three reasons. First, microbial activities and rates must be studied in situ. Second, many of the processes likely to affect sub-seafloor communities and activities are episodic [e.g., changes in fluxes of nutrients and electron donors (food)] due to volcanic events, earthquakes, or episodic release of hydrocarbons from deep reservoirs. Third, the process of entry into the sub-seafloor (e.g., by drilling) alters the environment and days to years are required for the environmental properties of fractured subsurface systems to return to stable background values.

Several different fracture-permeable environments are of interest for study of sub-seafloor life. These include:

(1) carbonate vent systems where H_2 and CH_4 are generated by interaction between seawater and mantle peridotite,

(2) sediment-rich continental margins where methane is produced and intermittently vented, and

(3) mid-ocean-ridge hydrothermal systems, where a variety of magmatic gases (CO_2, H_2, H_2S, SO_2, CH_4) are present.

Each of these types of venting systems operates in an episodic manner driven by unpredictable

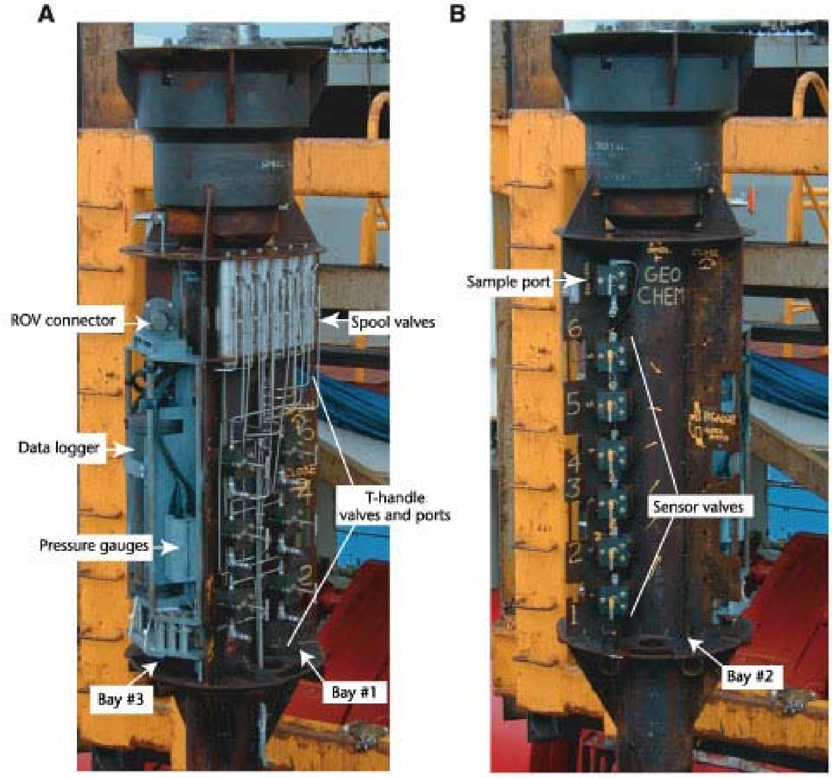


Figure 18. Cooperation between OOI and the Integrated Ocean Drilling Program (IODP) will provide exciting new opportunities to understand sub-seafloor microbial communities and processes in a variety of geologic settings. The OOI network can provide power and two-way, real-time data telemetry to these borehole observatories. Shown on the right are two views of the head of the IODP ACORK (Advanced Circulation Obviation Retrofit Kit) that has been designed to isolate multiple zones in a borehole for independent investigation. ACORKs allow sub-seafloor biosphere studies in the context of their hydrological, chemical, microbiological, and thermal regimes, as well as hydrologic responses to seismic ground motion, tides, and barometric loading. The RCO will link several existing borehole observatories on Juan de Fuca plate to the OOI network (Fig. 4).

geophysical or thermal events. The only means of studying these systems is to install the infrastructure and sensors necessary to detect these events, and to provide the capability to adaptively measure and sample remotely the microbial and biogeochemical changes induced by these events.

All components of the OOI (global, regional, and coastal) will contribute to better understanding of microbial communities, activities and significance in the ocean. The RCO, for example, will be particularly useful for studying sub-seafloor microbial processes. Node N1 is located on Hydrate Ridge and thus ideally located for studies of sub-seafloor microbes on a continental margin where methane is produced and intermittently vented. N4 on Axial seamount and N7 on Endeavour, as well as global site A3 on the East Pacific Rise will study microbial activity in the presence of active submarine volcanic systems (Fig. 17). RCO node N2 is located in a unique mid-plate setting far from any active plate boundary, and will help elucidate microbial processes on the vast abyssal seafloor. RCO nodes are excellent candidate sites for instrumented drill holes for studies of microbial communities, quantitative analyses of fluid chemistry and continuous measurements of temperature, pressure, and fluid flow (Fig. 18). The RCO is also a logical site to test new in situ instrumentation that will likely require, at least initially, more power than can be easily provided by moorings. The proposed global CND sites (Fig. 9) will also sample a wide range of ecosystems including regions of both high and low surface productivity at both mid and high latitudes. The high latitude sites, especially those in the Southern Ocean, are of particular interest since almost nothing is known about the microbial communities in these remote areas.

The use of ocean observatories for effective study of oceanic and sub-seafloor microbial systems will require integrated analyses of biological, chemical and physical properties. To maximize progress over the next ten years, complete characterization of these properties will require a long-term program of in situ analyses, paired with sampling for significant properties that are not currently measurable in situ. Sensors that detect biological properties are currently the least well developed instrumentation, but are critically important from both scientific as well as societal perspectives.

Existing in situ biological sensors consist largely of bio-optical devices that measure light scattering as a proxy for biological particles, or chlorophyll a (and other pigments) fluorescence as a proxy for phytoplankton. Biological sensors under development include in situ flow cytometers that measure light scatter and fluorescent properties of individual particles (Sosik et al., 2003) and genome-based sensors that detect DNA or RNA of different organisms. Genomic-based technologies continue to expand rapidly and many of the newest genomic and proteomic techniques have been successfully applied to laboratory studies of marine microbes. However, none of these technologies are currently used to study microorganisms in situ. The sensitivity, specificity and reliability of ocean-going biological sensors will require intense and accelerated development so ocean observatories can provide a maximum amount of information.

Molecular detection methods (gene chips and protein chips) can be used in situ to characterize aspects of genetic potential, community composition, and genetic expression. A variety of physical and chemical probes can be used in situ to measure key environmental properties, including temperature, chlorinity, chlorophyll content, and concentrations of key microbial products and reactants. For the foreseeable future, some key properties, such as microbial diversity and occurrences of unanticipated microbes, may require biological samples to be taken at appropriate intervals, fixed, and eventually retrieved. Osmotic samplers sample continuously and, after retrieval, allow a very broad range of chemical concentrations to be determined, including many chemicals not measurable by in situ analyzers. At sub-seafloor observatories, incubation arrays (e.g., polished rock chips, mineral-packed columns) will provide a direct measure of mineral weathering rates, biofilm development rates, and biofilm composition. Both biological samplers and chemical samplers can be retrieved and replaced during a standard maintenance trip to an observatory (e.g., once per year). These systems of combined in situ analyzers and samplers will document community composition and environmental context at individual points in time.

An exciting aspect of ocean observatories is that real time detection of particular events will allow sampling protocols to be modified "on the fly." For example, a sampling protocol could be modified in response to detection of a species of toxic algae (a relatively ephemeral event) to focus the sensor system on monitoring whether a full scale bloom is in progress or is simply a low level event. Likewise, episodic oceanographic or geological events could trigger a new set of observations related to the change in microbial populations and their physiological activity. The power of such event-driven strategies is extraordinary and opens broad new areas of investigation and knowledge generation about marine ecosystems, their functions and the factors that influence their ability to provide the ecosystem services that influence the global climate.

What controls the initiation and propagation of rupture along a fault, and thus the frequency and size of earthquakes?

The great Andaman-Sumatra earthquake in December 2004 illustrated how vulnerable coastal communities are to major earthquakes and associated tsunamis. While considerable progress has been made in forecasting and providing early warning for many types of natural disasters (e.g., volcanic eruptions, hurricanes, tornados), earthquake prediction remains beyond our reach. At present, plate tectonics provides a framework for understanding where earthquakes are most likely, but the processes that control the initiation and propagation of a rupture along a fault remain elusive. In spite of a number of false alarms, no consistent and reliable indicators of imminent rupture have been identified. The OOI will lead to better understanding of the fundamental physics of earthquake rupture, which should in turn lead to better estimates of seismic and tsunami hazards.

Although many earthquakes occur in the oceans, including the largest historical events, which have occurred on offshore subduction zones (e.g., Chile, 1960; Alaska 1964; Sumatra, 2004), studies of earthquake physics to date have focused on continental faults. This has been in large part due to the difficulty of making long-term observations in

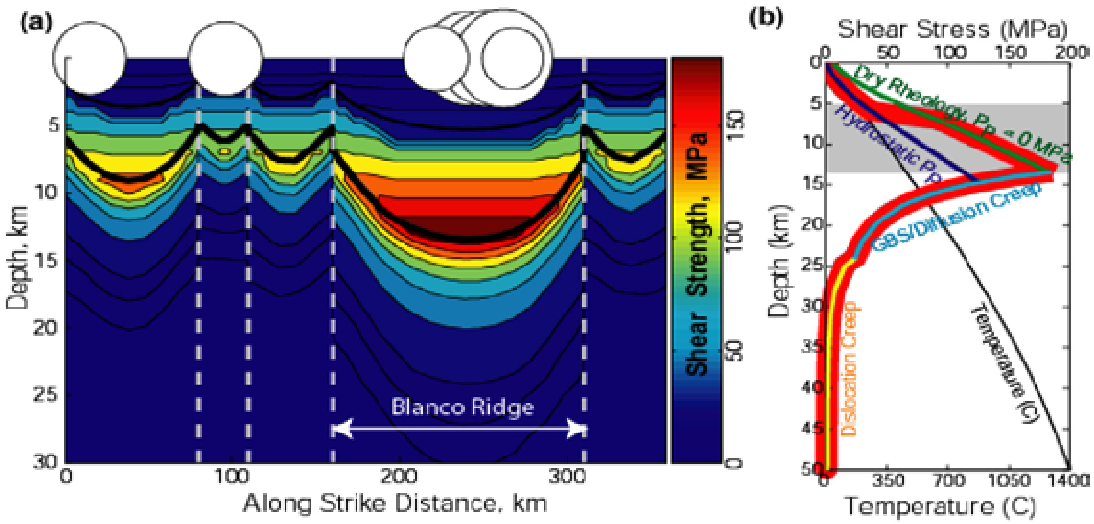


Figure 19. (a) Predicted maximum shear strength on the Blanco Transform Fault. Magnitude 6 and greater earthquakes (white circles) are plotted at their epicentroids and are sized assuming a stress drop of 1 MPa and that slip scales with rupture area. Black curves show the 250 °C and 600 °C isotherms and delimit the seismogenic zone. (b) Strength envelope (red) for the calculated geotherm at the center of the Blanco Ridge fault segment assuming a model with 3 km of ocean, hydrostatic pore pressure in serpentinized oceanic lithosphere from the seafloor to the 350 °C isotherm, and a dry peridotite mantle below this depth.

the ocean. The RCO will enable such observations. Examples of three complementary observations made by the RCO that will lead to a better understanding of earthquake physics and related processes are:

1) observations of earthquakes and related geodetic strain and fluid flow through an entire seismic cycle on a typical oceanic transform fault;

2) monitoring of seismicity associated with the "locked zone" of a major oceanic subduction zone; and

3) identification of fluid flow and/or seismicity triggered by distant tectonic activity.

The global component of OOI will contribute to this effort by expanding seismic and geodetic coverage to remote parts of the ocean basins, contributing to higher resolution models of mantle dynamics and lithospheric tectonics.

The seismic cycle on a transform fault: Node N3 of the RCO, which will support an array of seismometers and strainmeters on the eastern Blanco transform (Fig. 6), will provide a unique data set for understanding seismic activity and strain throughout the seismic cycle in an oceanic transform fault, and the knowledge thus gained should lead to new constraints for interpreting the behavior of continental transforms like the San Andreas fault. Since 1967, the eastern Blanco transform fault, which forms the southern edge of the Juan de Fuca plate, has experienced five magnitude 6-6.5 earthquakes, implying a recurrence interval of ~10 years. We can therefore expect to record at least one full seismic cycle during the lifetime of the RCO. The predicted temperature structure and rheology of the Blanco transform fault are shown in Figure 19. At present the initiation depth and fault propagation history of earthquakes is poorly constrained. Accurate earthquake hypocentral locations, seismicity patterns, waveform records and geodetic strain measurements will be used to constrain models of detailed faulting histories for the larger events. This will lead to improved understanding of the effects of temperature, rock rheology, and pre-existing fault geometry on earthquake initiation and propagation. Particularly interesting for potential earthquake prediction is the suggestion that ocean transforms show distinct precursory seismic activity (McGuire et al., 2005).

The Cascadia megathrust: Paleoseismic data acquired over the past decade indicate that the Cascadia subduction zone has repeatedly experienced "great" earthquakes and tsunamis in the past (i.e.

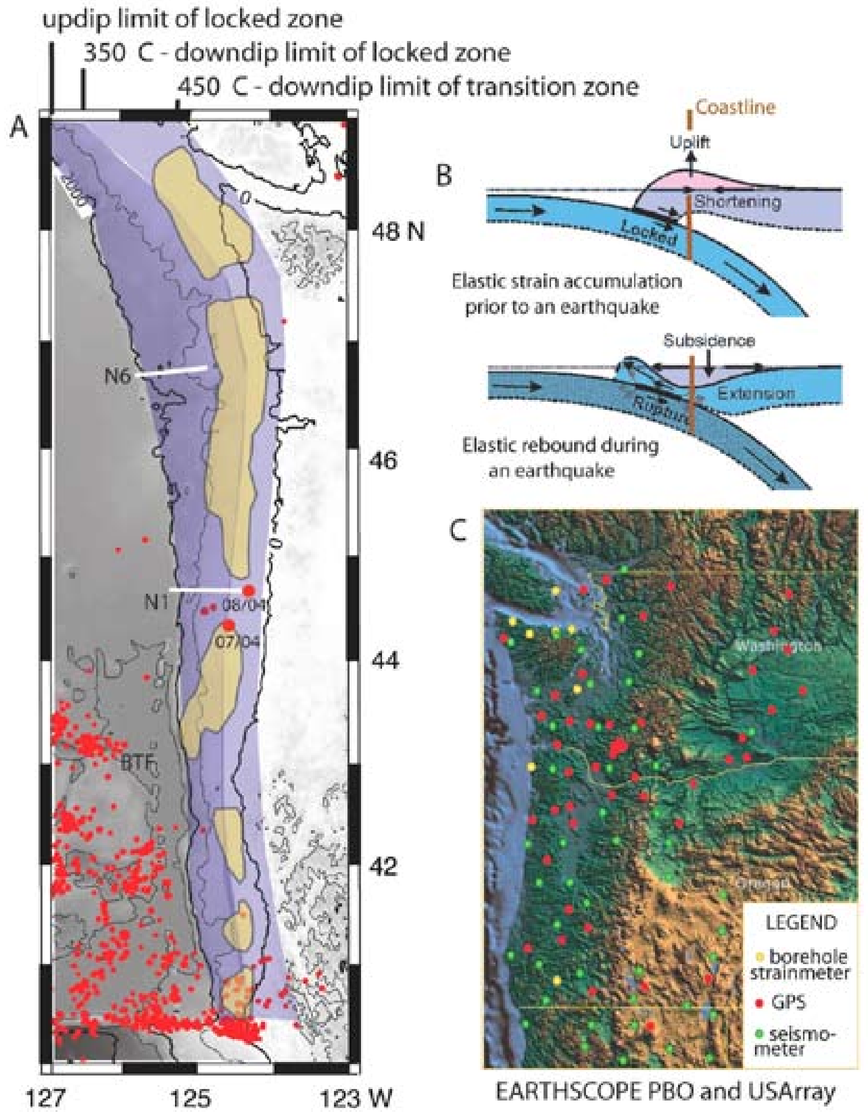


Figure 20. (a) The Cascadia subduction zone deformation front is located at the base of the continental slope, and the plate boundary dips east beneath the continental margin. The extent of the locked zone, as determined from thermal and geodetic modeling, is shown by grey shading. Based on comparisons to other subduction zones, seismogenic faulting is thought to be limited to the locked zone, although rupture in large earthquakes may propagate into the "transitional" zone. Red dots are earthquakes with magnitude >3.5 that have occurred since 1999. Deep basins, shown as gravity lows, are outlined in yellow (from Wells et al. 2003). In other subduction zones, large earthquakes often seem to nucleate at gravity highs and propagate across the gravity lows. The two seismic and geodetic transects across the subduction zone that are included as part of the RCO CND are shown (N1, N6) BTF – Blanco transform fault; HR – Hydrate Ridge. (b) Schematic cross-section showing topographic changes resulting from strain accumulation and release during an earthquake cycle. Topographic changes, which can generate tsunamis, are primarily offshore. (c) EarthScope geodetic and seismic stations active in the Pacific Northwest on July 7, 2006.

earthquakes of magnitude comparable to the recent Sumatra event of 2004). The interval between events varies from 200-1200 years, with the most common interval being 300-400 years (Goldfinger et al., 2003; Kelsey et al., 2005). The most recent large event occurred in January, 1700 (Satake et al., 1996). While we cannot be assured that the next "great" Cascadia earthquake will occur during the lifetime of the RCO, seismic and geodetic observations from the nominal "locked" zone (Fig. 20 a, b) are needed to determine whether the fault is truly locked or whether motion between the onshore Cascadia block and the subducting Juan de Fuca plate is accommodated by creep and aseismic slip. These data, from RCO Nodes N1 and N6 (Fig. 6) will also provide constraints on expected deformation of the seaward edge of the accretionary complex. Deformation of the outer accretionary wedge is likely more complex than illustrated in the simple cartoon of Figure 20b because of poroelastic and anelastic effects, but understanding of the response of this region is critical for estimating tsunami potential.

It is important to note that the nominal locked zone, which has been predicted based on geodetic data, thermal modeling, and knowledge of crustal structure obtained from active source seismic experiments, lies entirely offshore. Onshore, one of the more exciting developments of the past decade is recognition of episodic tremor and slip (ETS), which represents periodic slip on the plate boundary downdip of the locked zone accompanied by seismic activity within the Cascadia plate. Offshore instrumentation is needed to determine the response of the locked zone to loading by ETS. The seismic and geodetic instrumentation of the offshore plate boundary enabled by the RCO (Nodes N1 and N6 and extension cables from those nodes across the continental slope) therefore represent a critical complement to the extensive seismic and geodetic instrumentation on shore represented by Plate Boundary Observatory (PBO) component of EarthScope (Fig. 20c).

Tectonic teleconnections: In recent years, there has been growing evidence, both on land and at sea, that distant earthquakes can affect pore fluid pressures and, in some cases, trigger earthquakes. The mechanisms responsible for such "tectonic teleconnections" are poorly understood but are likely related to non-linear poro-elastic effects and may have fundamental implications for fluid transfer and between the subsurface biosphere and the ocean. Understanding of fluid flow and seismicity induced by distant events is presently limited by the scarcity of observations. For example, it was only through serendipity that an earthquake occurred in Middle Valley on the Juan de Fuca Ridge at the same time as a CORK was recording fluid pressures in a nearby borehole (Davis et al., 2004) or that temperatures were being recorded at a vent on the Gorda Ridge during a large earthquake on the Blanco transform (Dziak et al., 2003). Establishment of long-term seafloor and subseafloor hydrologic observatories along the plate boundaries (e.g. RCO nodes N1 at Hydrate Ridge; N3 on the Blanco transform; N4 at Axial Seamount) and in the interior of the Juan de Fuca plate (RCO node N2) will, for the first time, provide a comprehensive view of these processes. All of the RCO nodes, which should be instrumented with broadband seismometers, are important for recording waveforms from earthquakes. Instrumentation designed to monitor seafloor and subseafloor fluid pressure and venting, which is planned for several nodes (e.g. N1 extension at Hydrate Ridge in the accretionary complex, N4 at Axial Seamount), will provide multidisciplinary data to document and understand these phenomena.

5. Impact of OOI on Technology for Access to the Sea

The engineering challenges that must be addressed in the design, construction and operation of ocean observatories will stimulate the development and application of cutting-edge technology that will transform how ocean research is conducted in the coming decades. There are four principal areas in which this is already occurring:

1) improving the design and implementation of highly reliable, remote instrumentation that can operate unattended for long periods in the hostile ocean environment;

2) developing the cyberinfrastructure necessary to remotely control in situ sensors and deliver real-time or near-real-time data from anywhere in the world's ocean directly to a scientist's desktop;

3) stimulating the development of mobile, autonomous vehicles, both powered and unpowered, to extend data coverage around a fixed observatory and respond to episodic events; and

4) driving the design of new sensors (especially chemical and biological sensors) required for making for in situ measurements in the oceans.

Many of the technologies required for ocean observatories have obvious applications for environmental monitoring, homeland security and military surveillance, and many commercial spin-offs are expected from the engineering development required for ocean observatories.

Ocean observatory physical infrastructure: The engineering challenges for the design and construction of a sophisticated undersea infrastructure that serves power, data communications, and accurate time to a constantly changing suite of remote sensors are unprecedented in scope and complexity. While various commercial and government systems have been built that achieve some of the required engineering goals of OOI, none approaches the level of complexity of an ocean observatory system. For example, the submarine telecommunications industry builds extremely reliable undersea hardware to facilitate high bandwidth data transport between a small number of fixed

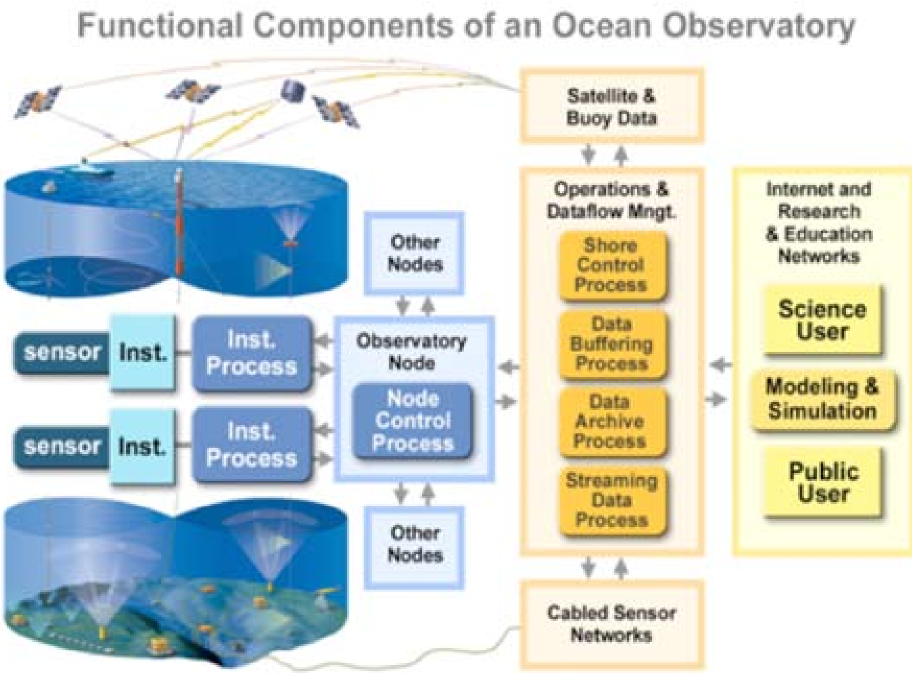


Figure 21. Illustration of the functional components of an ocean observatory cyberinfrastrure.

terrestrial terminals, but has not grappled with the issues of delivering power or communications at distributed points on the seafloor. NOAA has long operated autonomous surface weather buoys, but with the exception of a small number of tsunami warning buoys, their mission does not require high-bandwidth, two-way communication to sensors on the seafloor. The engineering challenges presented by the OOI will be addressed through new partnerships between industry and ocean scientists and engineers. By providing substantial power and two-way communication to sensors in the water column and on the seafloor, OOI will enable innovative new approaches to study ocean processes as described in Section 4.

Ocean observatory cyberinfrastructure: While the hardware engineering challenges of ocean observatories are substantial, implementing a software framework within which ocean observatories can operate also poses a significant challenge. The OOI cyberinfrastructure will connect the sensors and associated infrastructure in the ocean with data servers and archives on land, and human (or machine) end users (Fig. 21). This cyberinfrastructure represents both an essential integrating element of the ORION observatory system and a cutting edge information technology research topic.

The cyberinfrastructure the OOI is developing will serve as a model for a wide range of environmental observing systems. It will be designed to:

- *handle streams of real-time data 24/7/365 with data volumes ranging from kilobytes to terabytes*
- *deal with multidisciplinary data streams from large numbers of diverse sensors*
- *provide interactive control instruments for in situ experiments and event response*
- *facilitate assimilation of real-time data into models*
- *establish virtual observatories to facilitate interdisciplinary research across a range of spatial and temporal scales*
- *facilitate collaborative discovery by groups of researchers by providing advanced tools for data discovery and visualization*

No prior project has addressed autonomous management of sensor networks in the ocean, nor has any group attempted to bind all of these elements together into a working system. The development of ocean observatory cyberinfrastructure will not be a single step engineering effort, but rather will continue throughout the life of ocean observatories driven by a combination of continuing progress in in-

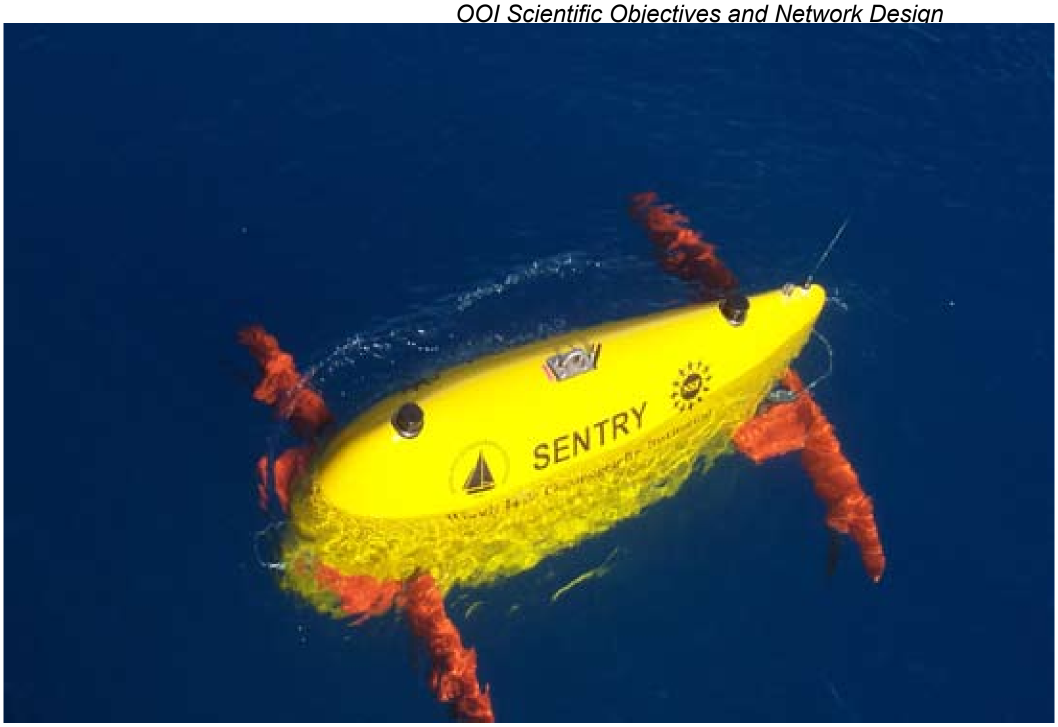


Figure 22. An example of a "next generation" autonomous vehicle that will be a key element of ocean observatory systems for both event response and for characterization of the volume of ocean around an observatory node.

formation technology and changing requirements in response to an evolving experience base and newly emerging science questions.

Mobile platform development: Ocean observatories (whether a buoy or a cabled node) will provide only a single site (or small number of sites) for scientific measurements on the seafloor or within the water column. In situ remote sensing methods (e.g., acoustic tomography) can provide some data between fixed sites over large ocean areas and volumes. However, direct and more detailed spatial sampling in the volume of ocean around a node to constrain scales of spatial variability poses a significant technological challenge. The development of sensor platforms capable of moving through the ocean volume, but which are connected to elements of the ocean observatory infrastructure (e.g., the power or communications system) either continuously or intermittently, will be a key to "expanding the footprint" of ocean observatories (Fig. 22). For example, gliders and AUVs are essential elements of the Pioneer Array that will be deployed as part of the coastal component of OOI to study shelf-break processes off the U.S. East Coast (Fig. 5). Repeat glider profiles will provide regional in situ measurements of ocean properties along the entire West Coast of the U.S. Platforms that can be remotely commanded to investigate episodic events will be an essential element of an event detection and response system, enhancing opportunities to capture key events that do not occur in the immediate vicinity of an ocean observatory. Docked AUV that are designed to respond to volcanic and tectonic events at spreading centers are planned the global mooring site at EPR 9°N (global site A3) and RCO nodes N4 (Axial Seamount) and N7 (Endeavour segment) on the Juan de Fuca Ridge.

Ocean observatories will stimulate engineering innovation in autonomous vehicles. For example, the current generation of deep ocean AUVs are capable of autonomous deployment for a couple of days covering distances of order 100 km, but extending either parameter will require an improved in situ power source, improvements in vehicle reliability (which poses a wide range of control, mechanical component, and corrosion issues), vehicle navigation, and the ability to upload data from and download instructions to the vehicle. Docking stations could provide the capability to recharge vehicle batteries and provide data connectivity, but are still in the early stages of development. A wireless communications system that can maintain contact with a moving platform would be even more enabling. Acoustic communication at low bandwidth over ranges of a few km is currently feasible, but the low bandwidth precludes transmission of imagery and the high latency limits real-time control. Future development of optical modem technology could extend this to many Mbit s^{-1} over ranges of order 100 m, and networks of optical modems wired together and into the ocean observatory backbone could provide areal or volume coverage over areas of interest.

Sensor development: Expeditionary research has traditionally relied heavily on the recovery of samples for subsequent shipboard or shore-based analysis, often many months after the samples are collected. Ocean observatories will promote the in situ measurement of physical, chemical and biological properties. In situ measurements are the only effective way to measure changes in ocean properties in real-time or near real-time. In some disciplines, sensor technology is relatively advanced; for example, seismic sensors with noise levels below ambient and with very wideband response are commercially available. In general, sensors for the measurement of physical quantities (e.g., position, velocity, acceleration, temperature, pressure, salinity) are relatively mature and robust in comparison to those that measure chemical or biological properties.

Because a key goal of ocean observatory research is the resolution of change on interannual or longer timescales, a significant effort to improve long term sensor stability and provide an in situ calibration capability will be needed. Many chemical sensor technologies used on land (e.g., laser-based atomic and molecular or magnetic resonance spectroscopy) require a significant amount of power that presently precludes their use in most autonomous applications. Ocean observatories offer a large increase in user power, and hence will provide a base for the application of these techniques in the ocean. This inevitably will drive the sensor technologies in a smaller, lower power, cheaper direction and in turn increase their utility for ocean sciences research. In a similar vein, the existence of ocean observatories will accelerate the transition of many genomic technologies from shore-based laboratories to in situ operation in the ocean, enabling exciting new directions in in situ marine biology.

6. Impact of OOI on Advancing Education and Public Awareness of the Oceans

A report issued this year by the National Academy of Sciences (NAS, 2006) highlights the importance of science, engineering and math for future economic competitiveness and also points to the declining interest in science, engineering and math training among U.S. students at all levels of education. A key finding of the report is that the U.S. must compete in the future by "optimizing its knowledge-based resources, particularly in science and technology…" The conclusions of this new report are not dissimilar to those reached in 1983 in A Nation at Risk (National Center for Excellence in Education, 1983). Since the 1983 report, there has been an outpouring of books and reports promoting new visions for science, technology, engineering and math (STEM) education. As summarized in the report of a recent NAS-sponsored workshop report, many of the new visions for science education contained key common elements that need to be better implemented:

- *conceptual understanding is more important than memorizing terms and facts;*
- *students need to learn how to apply knowledge to new situations;*
- *students need to learn how to design and conduct experiments;*
- *students need to learn the process of analyzing and interpreting data, including concepts of variability and uncertainty;*
- *students need to learn the process of investigation and discovery, including the scientific method - what it means and how it differs from advocacy; and*
- *synergies among scientific disciplines need to be understood and appreciated.*

The ORION Program is committed to providing "easy access to observations by the science and education communities" and the ORION strategic plan for education and outreach incorporates the six elements listed above. The plan will ensure that the research discoveries, technology innovations, unique near real-time information streams and interactivity of the ORION infrastructure are used

to engage young and old in ocean exploration and discovery; address key needs of the U.S. public education system; and identify and address critical graduate and continuing education issues affecting the ocean science and technology workforce.
A key component is the Data Translation and Visualization (DTAV) Facility. DTAV will generate and distribute real-time, near real-time, and event-driven information featuring user-friendly visualizations accompanied by engaging content. These products will be designed for use in a broad range of venues, including classrooms, science centers, Internet sites, television and radio, and community programs for children and adults. ORION data will flow to the DTAV facility via the ORION cyberinfrastructure. In particular, DTAV will be designed to develop the kinds of data-visualization products that pedagogical research has shown to be most effective. Many people are visual learners, and it is extremely important to create graphic manipulations of data, analysis, and modeling in order to develop deeper conceptual understandings in mathematics and science. Thus, ready access to ORION data and visualizations in useful forms is of special interest to educators.

7. Relevance of OOI to IOOS, GOOS, and GEOSS

ORION is part of a broader national and international effort to establish long-term observatories in the oceans and on land. The OOI and the ORION Program are the National Science Foundation's contribution to the Integrated Ocean Observing System (IOOS). The OOI facility is being designed to facilitate new approaches for studying the oceans that will lead to major advances in understanding of ocean system processes. IOOS will enhance existing coastal and deep ocean infrastructure and fuse data from existing observational systems from 13 Federal Agencies, with the goals of preserving healthy ecosystems, managing resources, mitigating natural resources, forecasting climate variations, and ensuring public health.

ORION and IOOS are essential components of a unified effort to further our understanding of ocean processes and applying that knowledge to the benefit of humankind. The OOI's novel technological developments in hardware and software will be critical to the success of IOOS. Advancements in cyber-infrastructure and modeling and technologies that develop and mature through ORION will enable IOOS to meet its long-term operational goals. Research addressed through the OOI facilities will be enhanced by the broader coverage of measurements provided by the IOOS network. Coordination and interoperability of the ORION and IOOS data management will allow users of both systems to access all data seamlessly. In turn, IOOS will provide a larger framework of observations through routine and operationally robust instruments and infrastructure, in which the results of process-oriented ORION experiments may be interpreted. These fundamental differences require the OOI operate within the flexible and rapidly changing research environment while the IOOS will operate in the less flexible, operationally oriented mission environment.

Both IOOS and OOI are essential components of a broader national and international effort to establish a global Earth observing system: Global Earth Observation System of Systems (GEOSS). On February 16, 2005, 61 countries agreed to a plan that, over the next 10 years, will revolutionize the understanding of Earth and how it works. Agreement for a 10-year implementation plan for a Global Earth Observation System of Systems, known as GEOSS, was reached by member countries of the Group on Earth Observations at the Third Observation Summit held in Brussels. Nearly 40 international organizations also support the emerging global network.

The GEOSS project will help all nations involved produce and manage their information in a way that benefits the environment as well as humanity by taking a pulse of the planet. ORION and other NSF-led observatory programs such as Earthscope and NEON will contribute new ideas, instruments and technology to the GEOSS effort eventually leading to enhancements and improvements of the initial system.

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