

The cover features a blue and yellow background with a stylized horizon line. Large, semi-transparent circular arrows in white and blue are scattered across the page, some pointing clockwise and others counter-clockwise, creating a sense of movement and interconnectedness. The text is centered and uses a bold, sans-serif font.

OCEAN OBSERVATORIES INITIATIVE

Science Plan

**Revealing the Secrets
of Our Ocean Planet**

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OCEAN OBSERVATORIES INITIATIVE

SCIENCE PLAN



REVEALING THE SECRETS
OF OUR OCEAN PLANET

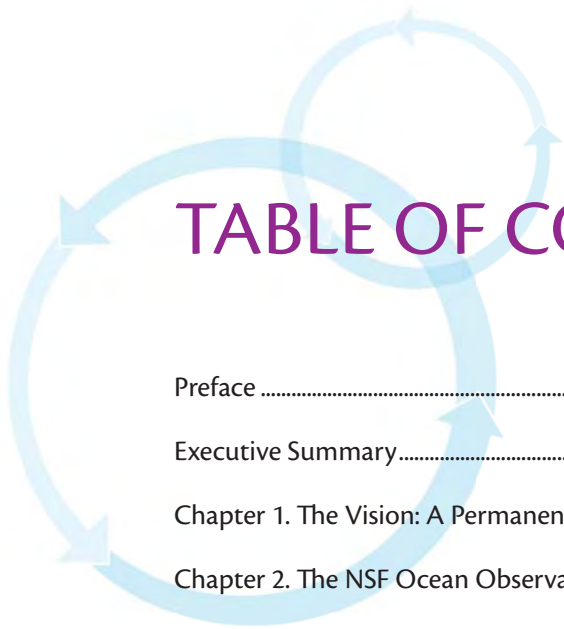
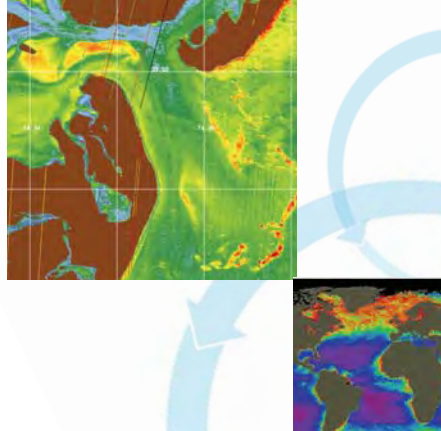


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PREFACE

This document presents the Science Plan for the National Science Foundation's Ocean Observatories Initiative (OOI). The OOI, and 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 goal of the OOI is to deliver an interactive, globally distributed and integrated observatory network to enable next-generation studies of the complex, interlinked physical, chemical, biological, and geological processes operating throughout the global ocean. This document is designed to offer a broad overview of a representative set of cutting-edge scientific drivers for ocean observatories, a description of the novel suite of new technological capabilities that OOI will provide for ocean research, and a summary of the important scientific, educational, and societal benefits to be gained by deploying this transformational new infrastructure.

This Science Plan was prepared by the ORION Program Office and the Executive Steering Committee of the ORION Program. Others who assisted with the preparation of parts of this document by contributing text, figures, or comments include John Allen, Manuel Barange, Alan Chave, Yi Chao, Robert Detrick, Gary Egbert, Sharon Franks, Dale Haidvogel, Dave Karl, Deborah Kelley, Alexander Kurapov, Jennifer Matthews, George Matsumoto, Janice McDonnell, Blanche Meeson, Cheryl Peach, Nancy Penrose, Véronique Robigou, Chris Scholin, Heidi Sosik, and Mark Stoermer. This document draws heavily from many earlier workshops and meeting reports, but we wish to specifically acknowledge the ORION Workshop held January 4-8, 2004 in San Juan, Puerto Rico co-chaired by Oscar Schofield and Margaret K. Tivey. We also wish to thank the OOI Science Plan Review Committee for their thorough and constructive review of this document. Review committee members included Harry Bryden, Kenneth Coale, Steve Emerson, Dave Karl, Larry M. Mayer, Marcia McNutt (Chair), Harvey Seim, and Heidi Sosik.

K. H. Brink
ORION Program Director
January 24, 2005

EXECUTIVE SUMMARY

The quality of life on Earth is determined in large part by a set of partially understood and interacting environments and processes that operate in the world's oceans. This complicated system, covering two-thirds of the planet, modulates both short- and long-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 with storms or tsunamis. The Ocean Observatories Initiative (OOI) is designed to enable powerful new scientific approaches for exploring the complexities of Earth-ocean-atmosphere interactions to accelerate progress toward the ultimate goal of understanding, and eventually managing, our planetary environment.

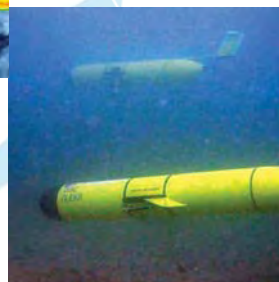
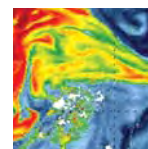
More than a century and a half of ship-based expeditionary research and three decades of satellite observations have successfully provided basic descriptions of the oceans and their interactions with terrestrial and atmospheric systems. The discovery of plate tectonics, the delineation of major ocean circulation patterns, and documentation of the coupled ocean-atmospheric interactions that lead to the El Niño/Southern Oscillation (ENSO) are all examples of results obtained from ship-, moored buoy-, or satellite-based studies.

As 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 sampled or studied using these traditional tools. Ship-based studies, for example, are very limited in their ability to investigate episodic events or to study dynamic systems that change over time periods longer than a few months. The signal levels associated with some phenomena (e.g., secular changes in temperature of the

ocean or the motions of tectonic plates) are small compared to background noise and require measurements over months to years just to resolve a signal. Some critical processes occur only during certain times of the year or during events, such as storms, when measurements from shipboard platforms are simply not possible. Although satellite observations have provided oceanographers with a unique synoptic, global perspective on the ocean, they remain primarily limited to measuring properties at the air-sea interface and in the uppermost ocean. The absence of long-time-series sites is particularly acute in the remote Southern Ocean where few *in situ* oceanographic or geophysical measurements of any kind are currently made on a routine basis. Consequently, even after many decades of study using ships and satellites, the global ocean is still poorly explored and its complex behavior is not well understood.

A New Approach

Driven by the need to address these limitations, the oceanographic community is poised to embark on a novel and revolutionary approach for studying the ocean that calls for the establishment of an interactive, globally distributed and integrated network of sensors in the ocean. This network is part of a broader trend in the physical and natural sciences toward use of arrays of *in situ* sensors, real-time data, and multidisciplinary approaches to study complex natural systems.



This new approach requires tools to collect extensive space- and time-referenced data in the oceans on co-evolving physical, chemical, geological, and biological processes at all relevant scales. Permanent sensor networks are needed to detect and study short-lived episodic events as well as to resolve, quantify, and explain longer-term changes in the oceans. Reacting to changes observed in real time or near real time will require sophisticated, interactive sensors and sampling devices. In some cases, *in situ* perturbation experiments will be needed to explore how complex natural systems respond to known changes. Also needed is the ability to recover samples remotely and analyze their properties *in situ*. Measurements will be required year round in even the most remote and hostile parts of the ocean; these observations will need to be continued for years or decades. Providing reliable predictions of processes operating in the oceans or on the seafloor depends on the development of modeling and simulation capabilities that use real-time data to test and refine those models. And, finally, anyone—researchers, students, educators, government, industry, and the general public—should have access from their desktops to near-real-time ocean observatory data, 24/7/365.

This emerging requirement to study the global ocean interactively and adaptively requires new technology and a new paradigm for doing ocean research. This paradigm will exploit two classes of tools: (1) innovative ocean observatories that provide unprecedented levels of power and communication to operate and manipulate real-time sensors located at fixed sites for years or decades, and (2) mobile ocean-observing systems that will provide broad spatial coverage, albeit with limited power and usually more restricted real-time data telemetry capabilities. These two complementary approaches—one focused on acquiring high-resolution time-series records at fixed sites, the other on obtaining broad spatial coverage using mobile platforms—are essential for studying ocean processes in both time and space.

This new technology will not replace shipboard expeditionary research, but it will open a new window from which to observe ocean and seafloor systems. Together these complementary research strategies will transform oceanography in the coming decade, changing in fundamental ways the manner in which marine science is conducted, and provide exciting new avenues through which to convey the importance of the oceans to a wider audience.

The Ocean Observatories Initiative (OOI)

The importance of establishing an ocean-observing capability has long been recognized and was re-affirmed in late 2004 by the U.S. Commission on Ocean Policy (see www.oceancommission.gov). In the last decade, a number of national and international programs have been developed that are concerned with observing the oceans. Their missions are to conduct fundamental research into important ocean processes and to provide timely, useful, and practical information to a variety of users in areas such as fisheries management, maritime shipping and safety, public health, homeland security, tsunami warning, and weather and climate forecasting.

The Ocean Observatories Initiative (OOI) is the National Science Foundation's contribution to this broader effort to observe the oceans. The OOI will design, test, and install pioneering ocean-observatory technology for the research-driven Ocean Research Interactive Observatory Networks (ORION) Program. The OOI and ORION are aimed at developing the new knowledge and technologies that will advance understanding of fundamental ocean processes. Fostering advances in basic knowledge and developing new technology is NSF's mission, and is the underlying goal of the OOI and ORION Program.

The OOI will deliver an interactive, globally distributed and integrated observatory network to enable next-generation studies of the complex, interlinked processes op-

erating throughout the global ocean. This initiative has been developed based on recommendations from more than 30 workshop reports and planning documents dating back to 1988, including two reports from the National Academy of Sciences (National Research Council, 2000; 2003), a number of widely attended national and international workshops, and a variety of more focused science, engineering, and outreach-oriented meetings and activities (Appendix 2). The OOI is designed to ensure that the research community in the United States has the infrastructure required to maintain its leadership role in Earth and ocean sciences for decades to come.

In 2000, the National Science Board approved the OOI as a Major Research Equipment and Facilities Construction (MREFC) account project. The President's budget for FY2006 called for funding of OOI beginning in FY2007 with approximately \$269M provided over a six-year period. The OOI comprises a number of major investments, including support for the fixed observatory infrastructure (cables, moorings, junction boxes), project and data management, cyberinfrastructure, and certain core instrumentation. This infrastructure will support the larger ORION Program, which will fund the operation and maintenance of observatory infrastructure; the use of observatories in ocean research; most observatory instrumentation, including development of new sensors; the use of mobile platforms such as gliders, profiling floats, and autonomous underwater vehicles (AUVs); and related education and outreach activities.

The OOI has three major observatory elements that cover coastal, regional, and global spatial scales. These elements are linked by a common instrument, infrastructure, and information-management system:

- The **Global Ocean Observatory** comprises a set of highly capable interactive moored buoys sited around the world's ocean in places where surface-to-bottom ocean data needs are greatest. These observatories will con-

sist of large, rugged, self-powered, telemetering buoys where scientific need dictates high data-return rates and power requirements, and simpler, but still very capable, designs for other settings.

- The **Regional Cabled Ocean Observatory**, in cooperation with ongoing Canadian efforts, will instrument an entire tectonic plate at key locations in the Northeast Pacific offshore northern California, Oregon, Washington, and Vancouver Island. A permanent electro-optical seafloor cable will connect multiple seafloor nodes that will provide power (tens of kW) and high bandwidth (data transfer rates of 10-100 Gbps) for the sensors, instruments, and underwater vehicles, allowing access to surrounding waters from the seafloor to the sea surface.
- The **Coastal Ocean Observatory** will provide sustained, but adaptable, access to dynamic and heterogeneous coastal systems. Fixed arrays of Endurance lines will provide continuous observations at widely distributed locations to document events and long-term changes, while relocatable Pioneer arrays will provide a flexible capability to focus on key processes in optimal configurations.

A system-wide **cyberinfrastructure** will allow users to remotely control their instruments, enabling adaptive strategies; perform *in situ* experiments; construct virtual observatories of suites of sensors specifically tailored to scientific needs; and access data in near-real time from almost anywhere in the world's oceans.

Science Drivers

This cutting-edge technology will enable novel and exciting research on a wide range of topics in the Earth and ocean sciences. All marine science disciplines will benefit from the OOI infrastructure as processes that could previously only be inferred, such as short-lived episodic

events or longer-term change, will be observed directly. Five topical areas representative of the kinds of fundamental, interdisciplinary research that the OOI will facilitate include:

- **Climate variability, ocean food webs, and biogeochemical cycles.** Understanding global climate dynamics and biogeochemical cycling requires data spanning an extraordinary range of spatial and temporal scales that cannot be obtained without a long-term, *in situ* presence in the oceans. The OOI will provide the infrastructure for making sustained measurements over decades at all three scales (coastal, regional, global) needed to quantify temporal variations in physical, chemical, and biological properties in the ocean. Near-real-time telemetry of time-series data will allow adaptive sampling in response to episodic events, which is necessary to detect non-linear interactions within the marine biosphere. The OOI time-series sites will complement other components of a global climate observing system including the Argo profiling float program and satellite missions.
- **Coastal ocean dynamics and ecosystems.** Most human-ocean interactions, including fish harvesting, transportation, recreation, and marine-related threats to life and property, occur in the coastal zone. Advancing understanding of coastal processes to use and manage these resources better, mitigate risks, and explore for new phenomena is challenging. Important controlling processes occur over a broad range of spatial and temporal scales and cannot be simultaneously studied with solely ship-based platforms. The OOI will make possible *in situ*, continuous measurements of longer-term changes in coastal ecosystems. Adaptive sampling in near-real time will elucidate the causes and effects of transient events such as harmful algal blooms and hypoxia, and the impact of human activities on the coastal ocean and its living resources.
- **Global and plate-scale geodynamics.** Critical gaps exist in global geophysical coverage in oceanic regions far from land, limiting studies of deep-Earth structure and dynamics. Autonomous, battery-operated instruments are also poorly suited to study episodic events such as earthquakes and volcanic eruptions along plate boundaries, most of which lie beneath the ocean. The OOI will provide the infrastructure necessary to install dense networks of continuously recording sensors in geologically active areas on the seafloor. A unique plate-scale observatory will be used to determine the redistribution of stress following large earthquakes, investigate how plate boundaries interact and deform, and assess hazards from these tectonic events to coastal populations. The OOI will also establish seafloor geophysical observatories that, in concert with land-based networks, will help complete the global coverage of geophysical observations and provide much-improved images of deep-Earth structure.
- **Turbulent mixing and biophysical interactions.** Turbulent mixing in the ocean plays a critical role in the transfer of heat and mass within the ocean, in the exchange of energy and gases between the ocean and atmosphere, and between the ocean and the seafloor. Horizontal and vertical mixing within the ocean also has 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. The OOI will provide the sustained time-series observations necessary to document variations in ocean mixing and marine ecosystems that are associated with interannual, and regional or global, changes in ocean circulation, and to study the infrequent, but intense, ocean-atmosphere interactions during major storms such as hurricanes.

- **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; interacts with hot, newly emplaced volcanic crust to form spectacular “black smoker” hydrothermal vents with their unique biological communities; concentrates massive reservoirs of methane and methane hydrates along continental margins; and hosts a vast, largely unexplored sub-seafloor microbial biosphere. There is increasing evidence that transient events—earthquakes, volcanic eruptions, massive slope failures—play a critical role in fluid-rock interactions and sub-seafloor microbial activity. These transient events, which may last only hours or days, are very difficult to observe and sample using conventional ship-based studies. Understanding 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 provided by the OOI infrastructure.

The engineering challenges that must be addressed in the design and construction of ocean observatories will also drive the development and application of cutting-edge technology for the field of oceanography. Four areas where this is already occurring include: (1) improvements in the design and development of highly reliable instrumentation and equipment that can operate unattended for long periods in the hostile ocean environment; (2) development of the cyberinfrastructure necessary to remotely manage sensors, data, and the observatory infrastructure; (3) use of mobile, autonomous vehicles and *in situ* remote sensing to extend the areal coverage and sample density around a fixed observatory; and (4) driving the design of new sensors for *in situ* measurements. Spin-offs in the academic, commercial, government, and military sectors can reasonably be expected to ensue

from all of these aspects of ocean observatories. Many of the technologies required for ocean observatories have obvious applications for military surveillance, homeland defense, and environmental monitoring.

Educational and Public Outreach Opportunities

The real-time data and high-speed, interactive communication capabilities of ocean observatories will open entirely new avenues for diverse student and public audiences to interact with and understand the natural world. Citizens of all ages will be able to participate in the journey of scientific exploration and discovery through a rapidly expanding array of online, interactive learning experiences that use data products from observatories. To exploit these opportunities, ocean scientists and educators are working together to ensure that educational and public outreach needs are factored into observatory planning from the beginning. An important element of this strategy will be developing working partnerships with a number of existing education programs in the marine sciences.

Part of a Broader Effort to Observe the Oceans

The OOI infrastructure and the research-driven ORION Program are part of a broader national and international effort to establish long-term observatories in the ocean, both for conducting basic research and for operational oceanographic needs.

At the national level, OOI/ORION’s closest relationship with operational ocean observational systems is with the proposed U.S. Integrated Ocean Observing System (IOOS). The primary goal of the IOOS is to maintain an integrated, sustained network of reliable, operational oceanographic sensors to provide a variety of products to specific users and the general public, and to distribute those products in a timely manner. The primary focus

of the OOI and the ORION Program is to develop new knowledge and technology to advance understanding of the oceans. While different in terms of motivation, the two programs share many common interests and are essential complements to one another. The advances in fundamental knowledge of ocean processes that OOI/ORION will uncover will be essential for IOOS to achieve its longer-term operational goals. OOI/ORION will also foster the development of new sensors and observatory technologies, including the capability to make observations in remote and extreme environments that can eventually be transferred to the IOOS operational network. At the same time, the IOOS observational backbone will provide a means for ORION researchers to place their results in a broader spatial and temporal context. To exploit the potential synergies between OOI/ORION and IOOS, these two programs will be closely coordinated at all stages, from inception and planning through installation and operation.

IOOS is being developed as a contribution to the international Global Ocean Observing System (GOOS), which in turn is a component of the international Global Earth Observation System of Systems (GEOSS). GEOSS is dedicated to the development of a comprehensive, coordinated and sustained Earth Observation System to collect and disseminate improved data and models to stakeholders and decision-makers. While GEOSS transcends the ocean sciences, the OOI represents a major ocean contribution to this new, international effort. For example, the fixed-point OOI time-series sites will complement the broad spatial coverage of upper ocean properties provided by mobile Argo profiling floats. The President's recent program to upgrade the global tsunami warning system motivates a significant expansion of the Global Seismic Network (GSN) to the oceans and the use of seafloor pressure gauges at global, regional, and coastal observatories.

Planning for other research-driven ocean observatory and observing programs has been underway in a number of other nations, much of it in close collaboration with

efforts in the United States. The OOI's closest international partner is NEPTUNE Canada, which is building a cabled observatory offshore of Vancouver Island. Other research-driven observatory programs exist in Japan (ARENA) and Europe (ESONET). Distributed sensor networks and observing systems are also being developed to address a broad range of Earth and environmental problems in the U.S. research community (e.g., EarthScope, NEON, CLEANER, CUAHSI). Although many of these efforts are not specifically oceanographic, the connections with OOI can, nonetheless, be very strong. The scientific planning, management, and operational structure of the OOI will be organized in a manner to leverage these other efforts into a truly global, environmental observatory.

Why Now?

There are three compelling arguments for why it is essential that the OOI move forward now to establish the next-generation, research-driven ocean observatories described above.

1. We must maintain the leadership role of the United States in ocean and environmental observing systems. Other nations (Japan, Europe, Canada) have made, or are planning to make, major investments in ocean observing systems in the next few years. If the U.S. research community does not have access to these same tools, it will not be able to pursue the most exciting and important questions in marine science.
2. The President's Commission on Ocean Policy has clearly identified many areas in which the oceans are in crisis, and it is essential that we act now to begin to address these issues. Improved understanding of all of these issues—the impact of pollution on coastal systems, managing the ocean's living resources, improving earthquake and tsunami hazard assessment, and others—will benefit from the new knowledge of ocean processes and observing technology that the OOI will develop.

3. We must build the OOI network now in order to leverage various research-driven and operational observing systems being developed in the United States and in other nations by coordinating ship time (for observatory installation, servicing, and maintenance), data management, and education and outreach efforts.

Intellectually, this shift from expeditionary to observatory-based research is driven by long-standing scientific problems and by new questions and hypotheses across a broad range of Earth and ocean sciences that cannot be addressed using more conventional approaches. Technically, this paradigm shift is feasible now because of major advances in several different fields, including evolving sensor development (encouraging *in situ* measurements of an ever-growing suite of physical, chemical, and biological properties); advances in communications technology (allowing two-way data communication via satellite or high-bandwidth fiber optic cable from anywhere in the world's oceans to a scientist's desktop); advances in power delivery systems (allowing instruments with much higher power requirements to be used routinely in marine experiments); and developments in cyberinfrastructure (providing the capability to manage large volumes of data in real time or near-real time and to control remote sensor networks interactively) and in the speed and miniaturization of computers, which will allow eventual deployment of very intelligent nodes on the network.

The OOI and the ORION Program build on the legacy of large oceanographic research programs that encouraged multidisciplinary approaches and collaborative investigations during the past 15 years (e.g., WOCE, JGOFS, RIDGE, ODP, GLOBEC, IRONEX, CLIVAR, CoOP). These programs provided training in interdisciplinary science, and developed hypotheses and raised questions about ocean systems that demanded a new investigative approach. The success and experience gained with pioneering observatory projects in both the coastal (e.g., LEO-15, MVCO) and open (e.g., HOT, BATS, TOGA-TAO, NeMO) ocean, as well as engineering knowledge gained in various pilot experiments and testbeds (e.g.,

MARS [United States], VENUS [Canada], and High-SeasNet), have laid the groundwork for the major investment in this new technology that is now being proposed.

The OOI represents a significant departure from traditional approaches in oceanography. It promises to transform the manner in which research is conducted in the oceans and expand our understanding of the role of the oceans in planetary processes. In particular, the OOI provides the infrastructure to integrate observations across vast scales from the microscopic and even submicroscopic (e.g., future DNA arrays deployed at observatories and the measurement of ground motion to the nanometer level) to the ocean-basin scale (e.g., for studies of ocean circulation, climate variability, and Earth structure). Data collected by ocean observatories will be fully open and available for use by researchers, educators, government, and industry. The paradigm shift in ocean research enabled by the OOI will open entirely new avenues of research and discovery in the oceans, foster the development and application of advanced technology to ocean science problems, provide exciting new opportunities for conveying the importance of the oceans to students and the general public, and acquire critical information for decision-makers in developing ocean policy.

CHAPTER 1. THE VISION: A PERMANENT INTERACTIVE PRESENCE IN THE OCEANS

Images of Earth viewed from space show that we live on an ocean planet (Figure 1.1). The oceans, which cover two-thirds of the surface of the planet, exert a dominant influence on life on Earth and play a critical role in many planetary processes. For example, the capacity of the oceans to absorb and release heat and greenhouse gases modulates short- and long-term climatic variations (Figure 1.2). The oceans contain greater than 50 times more CO₂ than the atmosphere. Thus, even small perturbations in the ocean carbon cycle can result in substantial

changes in atmospheric concentrations of CO₂, affecting global climate. Oceanic photosynthetic biomass amounts to <0.5% of the terrestrial biomass, but the uptake of organic carbon in marine ecosystems approaches 50% of the global total. The coastal ocean exerts a major influence on weather systems affecting the more than 50% of the human population that reside within coastal regions. More than 90% of the world's fish catch is harvested each year from coastal waters that support approximately 30% of marine primary production.



Figure 1.1.
View of the
“ocean planet”
from space.

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

Through the unknown, remembered gate,
Where the last of earth left to discover
Is that which was the beginning.

At the source of the longest river
The voice of a hidden waterfall,
Not known, because not looked for,
But heard, half-heard, in the silence
Beneath two waves of the sea.

T. S. Eliot, The Four Quartets, 1943

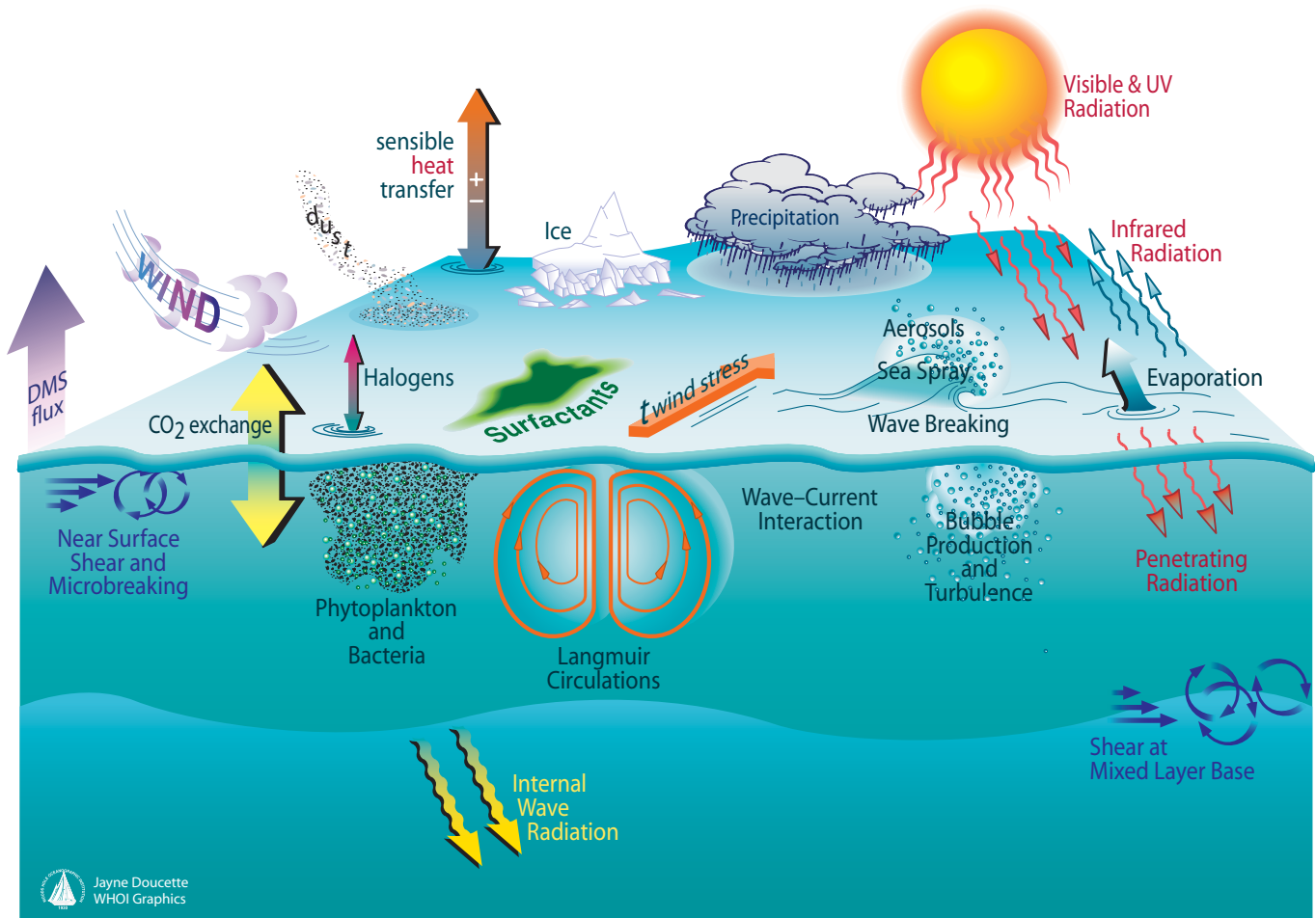


Figure 1.2. Depiction of processes operating at the air-sea interface and in the upper ocean mixed layer. Many of these processes vary on time scales ranging from seconds to decades and remain poorly understood.

Over geological time, the distribution, shape, and morphology of continents and ocean basins have been determined by the interplay among a small number of large tectonic plates (Figure 1.3). Virtually all mid-ocean ridges and most subduction zones on Earth lie below several kilometers of seawater within the ocean basins. These powerful, slow-moving tectonic plates are responsible for more than 70% of Earth's volcanic activity, generate the world's largest earthquakes, and occasionally produce tsunamis that devastate coastal populations. Within the last ten years, a vast, unexplored microbial biosphere has been discovered below the seafloor within the pores and cracks of the oceanic crust and in the overlying sediments. Not

only is this deep, hot biosphere important for understanding life and its origins on Earth, but similar underwater volcanic systems may be prime targets in the search for life elsewhere in the solar system.

To begin to understand the interplay among the complex, interlinked processes operating in the oceans, we must be able to make sustained and adaptable measurements throughout key portions of this dynamically changing system. The National Science Foundation's Ocean Observatories Initiative, part of a broader national and international effort to observe the world's oceans for a variety of purposes, will provide the basic

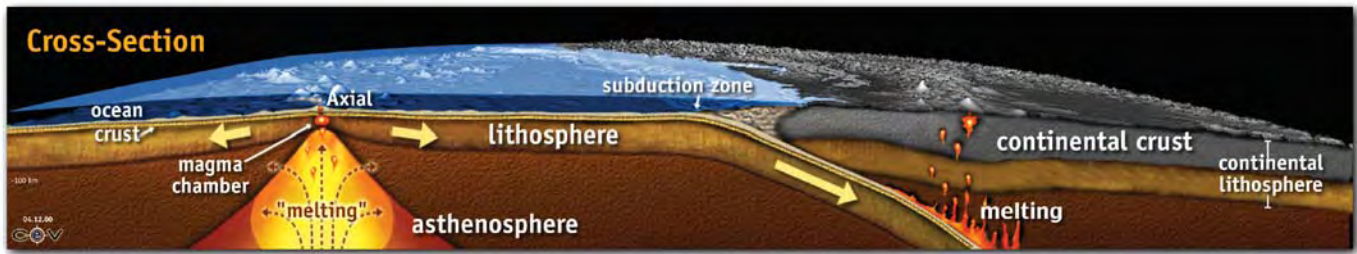


Figure 1.3. Portrayal of the plate-tectonic cycle. Many questions regarding global and plate-scale geodynamics remain unanswered because of the difficulty of making observations over the two-thirds of the planet covered by water, and the inability to instrumentally “capture” episodic events such as earthquakes or volcanic eruptions. Image provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and the Center for Environmental Visualization.

infrastructure to allow the oceanographic community in the United States, to remain at the forefront of research into how the Earth-ocean-atmosphere system affects the planet on which we live.

Limitations of Traditional Approaches for Studying the Oceans

More than a century and a half of ship-based expeditionary research and three decades of satellite observations have successfully provided basic descriptions of the oceans and their interactions with terrestrial and atmospheric systems. The discovery of plate tectonics, the delineation of major ocean circulation patterns, and documentation of the coupled ocean-atmospheric interactions that lead to El Niño/Southern Oscillation (ENSO) are all results obtained from ship-, moored buoy-, or satellite-based studies. As our understanding of the oceans has advanced, however, it has become increasingly apparent that many critical processes occur at temporal and spatial scales that cannot be effectively sampled or studied with traditional shipboard techniques, satellites, or a few short-term, widely separated stations.

Traditional approaches for studying the ocean, for example, are very limited in their ability to detect and characterize change occurring over time periods of years or de-

cadecades. Without sufficiently long time series in the oceans, it will not be possible to recognize many effects of human activity on the coastal ocean, determine the causal links between longer-term changes in ocean current heat transport and precipitation patterns on land, or study the effects of the absorption of atmospheric CO₂ on upper-ocean chemistry and the composition of marine phytoplankton communities. The signal levels associated with some phenomena (e.g., changes in sea level and ocean heat content or the motions of tectonic plates) are often so small compared with the background noise that measurements are required over long time periods, or over large spatial scales, simply to resolve a signal.

Ship-based studies are particularly limited in their ability to investigate the onset and immediate aftermath of episodic events such as earthquakes, submarine volcanic eruptions, or hurricanes. For example, observing and quantitatively measuring the discharge of exotic microbes into the deep sea in the hours or days immediately following a submarine volcanic eruption requires *in situ* sensors and sampling devices that can be activated automatically or on command from shore. Ship-based responses typically take weeks or months to mobilize, precluding a timely response to these kinds of short-lived events. Even where measurements from shipboard platforms are

feasible, during certain times of the year (winter at high latitudes) or during major storms, ship operations can't be conducted.

While satellite observations have provided oceanographers with 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. Many global-scale problems, for example, determining the structure and dynamics of Earth's interior or constraining the global flux of carbon from the upper ocean to the deep sea, require *in situ* measurements in the ocean or on the seafloor that satellites will never provide. The absence of long-time-series sites is particularly acute in the remote Southern Ocean where few *in situ* oceanographic or geophysical measurements of any kind are currently made on a routine basis.

A New Approach

The challenges of advancing understanding of the global ocean are formidable. Confronting these challenges requires a novel and revolutionary approach for studying the ocean that calls for the establishment of an interactive, globally distributed and integrated observational network in the ocean. Permanent sensor networks are needed to detect and study short-lived episodic events, as well as resolve, quantify, and explain longer-term changes in the oceans. Reacting to changes observed in real time or near real time will require sophisticated, interactive sensors and sampling devices. In some cases, *in situ* perturbation experiments will be needed to explore how complex natural systems respond to known changes. Also needed is the ability to recover samples remotely and analyze their properties *in situ*. Measurements will be required year round in even the most remote and hostile parts of the ocean; these observations will need to be continued for years or decades. Providing reliable predictions of processes operating in the oceans or on the seafloor depends on the development of modeling and simulation capabilities that use real-time data to test and refine those models. And, finally, anyone—researchers,

students, educators, government, industry, and the general public—should have access from their desktops to near-real-time ocean observatory data, 24/7/365.

This emerging requirement to study the global ocean interactively and adaptively requires new technology and a new paradigm for doing ocean research. This new paradigm exploits two classes of tools: (1) innovative ocean observatories that provide unprecedented levels of power and communication to operate and manipulate real-time sensors located at fixed sites for years or decades, and (2) mobile ocean observing systems, such as gliders or profiling floats, that provide broad spatial coverage, albeit with limited power and usually more restricted real-time data telemetry capabilities (Figure 1.4). These two complementary approaches—one focused on acquiring high-resolution time series records at fixed sites, the other on obtaining broad spatial coverage using mobile platforms—are essential for the study of ocean processes in both time and space.

This new technology will not replace shipboard expeditionary research, but will open a new window from which to observe ocean and seafloor systems. Together these complementary research strategies will transform oceanography in the coming decade, changing in fundamental ways the manner in which marine science is conducted, and provide exciting new avenues through which to convey the importance of the oceans to a wider audience.

Ocean Observatories and Observing Systems

The establishment of a capability for sustained ocean observations is both a national and international issue whose societal importance has long been recognized and re-affirmed in 2004 by the U.S. Commission on Ocean Policy (see www.oceancommission.gov). The realization of this goal—adequately and effectively observing the oceans—cannot be achieved by a single nation, by using a single approach or implementation strategy, or by a single program. Through foresight, planning, and cooperation under the auspices of the National Ocean Partner-

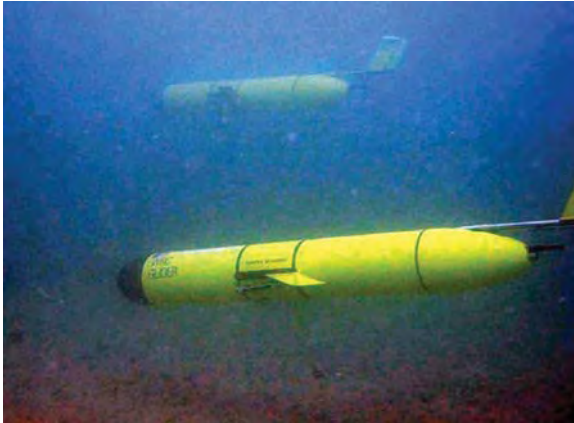


Figure 1.4. Gliders and other autonomous underwater vehicles (AUVs) will be used to expand the footprint around the fixed time-series sites established by the OOI. Left: The Webb Slocum glider is one of several AUVs that enable oceanographers to measure hydrographic, chemical, and biological fields on long sections across the oceans. Given a set of mission parameters, gliders follow them until they are changed, reporting data as often as they surface. Here, two Webb Slocum gliders are flying off the west coast of Florida during a red tide in January 2003. Photo courtesy of Oscar Schofield, Rutgers University. Right: REMUS AUVs configured with forward-looking, high-resolution sonar, a side-scan sonar, acoustic communication, and various other environmental sensors. AUVs such as these have proven especially useful in coastal surveys of bathymetry, currents, and water properties. Photo courtesy of Chris von Alt, Woods Hole Oceanographic Institution.

ship Program (NOPP), the oceanographic community in the United States has devised a strategy that divides the implementation blueprint into a number of manageable components. Each component is tailored to specific strengths of the participant organization, user community, or government mission agency. Each has a justifiable objective with benefits to the taxpayer, whether it be improving the short-term predictive capability of ocean models for better weather forecasting or building the knowledge base essential for advancing our fundamental understanding of ocean processes.

The last decade has seen the development of a number of national and international observing programs, both for conducting basic research in the ocean and for meeting growing operational oceanographic needs. IOOS is an operational observing system that is being planned through NOPP by Ocean.US (<http://www.ocean.us>). IOOS is designed to provide timely and practical information to a variety of users in areas such as fisher-

ies management, maritime shipping and safety, public health, homeland security, tsunami warning, and weather and climate forecasting. The coastal component of IOOS will be developed through a set of regional associations that will plan observing systems that adhere to national standards, but that are tailored to meet local needs. It is likely that coastal IOOS efforts will depend heavily on moored buoys. The open-ocean component of IOOS will incorporate both fixed moorings and mobile assets (e.g., gliders and profiling floats) that can provide information over broad areas of the global ocean. IOOS is being developed as a contribution to the international Global Ocean Observing System (GOOS) (<http://ioc.unesco.org/goos/>). GOOS incorporates *in situ* and satellite observations, modeling, and analysis of marine systems to provide accurate descriptions of the present state of the oceans and its living resources, as well as forecasts of future ocean conditions.

These efforts are all components of the international Global Earth Observation System of Systems (GEOSS) (<http://www.epa.gov/geoss/index.html>). GEOSS is dedicated to the development of a comprehensive, coordinated, and sustained Earth Observation System to collect and disseminate improved data and models to stakeholders and decision-makers. GEOSS was created at the G-8 summit in Evian, France, in June 2003. In April 2004, ministers from more than 50 nations, including the United States, formally adopted a ten-year implementation plan for a Global Earth Observation System. While GEOSS transcends the ocean sciences, the programs described above represent a major ocean contribution to this broader international effort.

The National Science Foundation, through its OOI and the larger ORION Program, have an important and unique role to play in this growing array of ocean observing programs. The focus of most of these operational observing programs is on using existing technology and knowledge to provide reliable information to meet the needs of mission agencies such as NOAA and NASA for improved weather and climate forecasting, fisheries management, or global monitoring. In contrast, NSF's OOI is aimed at developing new knowledge and technologies that will advance understanding of fundamental ocean processes. Fostering advances in basic knowledge and developing new technology is NSF's mission, and is the underlying goal of the OOI and the ORION Program.

While different in terms of motivation, the OOI and operational observatory programs such as IOOS share many common interests and are essential complements to one another. The continued delivery and progressive enhancement of the information products expected from IOOS over the long term will require major advances in intellectual understanding of ocean processes; in sensor technology, communications, and power systems; in data management, storage, and distribution systems; and in computational models and visualization systems. At the same time, the IOOS observational backbone, and related programs such as Argo, will provide OOI researchers with access to a broader spatial and temporal context

for their research. Obviously, vigorous pursuit of both paths will result in powerful synergies. To exploit these synergies, OOI and IOOS will be closely coordinated at all stages, from conception and planning through installation and operation.

Goals, Benefits, and Anticipated Outcomes

Through ocean observing programs like IOOS and OOI, the U.S. oceanographic community is developing a new strategy and capability to observe and study the oceans. These programs are an integral part of a broader national and international effort to establish a sustained observational presence in the ocean, both for conducting basic research and for operational oceanographic needs.

The OOI will incorporate coastal, regional, and global components into a coherent, evolving, interactive sensor network integrated through a common management system handling instruments, infrastructure, and data (Chapter 2). The OOI infrastructure will have the capability to detect short-term events, examine synchronicity of observations across broad spatial scales, and resolve longer-term changes in ocean systems.

All marine science disciplines will benefit from the OOI infrastructure because processes that previously could only be inferred, such as short-lived episodic events or longer-term changes, will be directly observed. In Chapter 3 of this document, we highlight a few examples of the advances that are anticipated from the development and implementation of a research-oriented ocean observing system. However, the new technology provided through the OOI will inevitably lead to new discoveries and scientific advances in understanding Earth and ocean processes that cannot even be imagined today. Naomi Oreskes, in her essay on the History of Earth Sciences (Encyclopedia of Physical Science and Technology, 3rd edition, Academic Press), has noted that "Advances in the earth sciences have been as much a function of improved communication and data collection as of improved theory. Often theory has followed advances in instrumentation and data-processing rather than the other

way around.” Large-scale data collection programs as exemplified by the OOI/ORION and IOOS are central to the future of ocean sciences.

As computer models capable of simulating complex systems gain in sophistication with advances in computer science and technology, synoptic views of ocean data become essential for assimilation and comparison. These observations will in turn stimulate the development of new generations of models of ocean processes. Data will flow ashore continuously from many sites, thus affording opportunities to test evolving models with real-time input. Furthermore, the incorporation of simultaneously obtained data streams from diverse disciplines will drive the integration of observations into advanced, more comprehensive descriptions of marine systems.

The engineering challenges that must be addressed in the design and construction of ocean observatories will also be a driver for the development and application of cutting-edge technology to the field of oceanography in areas such as cyberinfrastructure, sensor development, utilization of mobile, autonomous vehicles, and development of highly reliable instrumentation and equipment that can operate unattended for long periods in the hostile ocean environment (Chapter 4). Spin-offs in the academic, commercial, government, and military sectors can reasonably be expected to ensue from all of these aspects of ocean observatories. Many of the technologies required for ocean observatories have obvious applications for military surveillance, homeland defense, and future environmental monitoring.

The paradigm shift in Earth system science that will be generated by the innovative *in situ* networks and cyberinfrastructure required for ocean observatories also has the potential to invigorate U.S. science education (Chapter 5). Real-time information and robotic interactivity will also enable citizens of all ages to participate in the journey of scientific exploration and discovery, contributing to the goal of a well-informed citizenry that recognizes and values the research community’s drive to understand the complexities of Earth and ocean systems.

CHAPTER 2. THE NSF OCEAN OBSERVATORIES INITIATIVE

The Ocean Observatories Initiative is the National Science Foundation's contribution to an international effort to observe the global ocean. The OOI, a NSF Major Research Equipment and Facilities Construction (MREFC) project, will design, construct and install pioneering ocean observatory technology for the research-driven ORION Program. ORION is dedicated to developing a better understanding of the complex and interlinked physical, chemical, biological, and geological processes operating in the world's oceans.

The National Science Board approved the OOI as a MREFC project in 2000, and the President's budget in FY2006 indicated that funding for OOI is planned to begin in FY07 with about \$269M provided over a six-year period. NSF awarded a Cooperative Agreement to the Joint Oceanographic Institutions, Inc. (JOI, Inc.) for the ORION Program Office in early 2004. The 1201 Group, a joint undertaking by JOI, Inc. and the Consortium for Ocean Research and Education (CORE), is managing the overall project.

The relationship between the OOI and the ORION program is illustrated in Figure 2.1. The OOI comprises a number of different investments, including support for the fixed observatory infrastructure (cables, moorings, junction boxes), project management, data management, cyberinfrastructure, and certain core instrumentation. This infrastructure will support the larger ORION Program, which will fund the operation and maintenance of observatory infrastructure, the use of observatories in ocean research, most observatory instrumentation including development of new sensors, the use of mobile platforms such as gliders, profiling floats, and AUVs, and related education and outreach activities.

Planning for the OOI began more than a decade ago. Appendix 2 lists more than 30 workshops, written reports, and planning documents advocating the creation of a research-driven ocean observatory program. The earliest report in the series was published in 1988, seventeen years ago, and advocated a comprehensive network of seafloor seismic observatories to complement the Global Seismic Network (GSN) then under construction by the Incorporated Research Institutions for Seismology



Figure 2.1. Depiction of the relationship between the ORION Program and the OOI. The light-colored circle represents the infrastructure portion of the program funded by the OOI, approximately \$269M, which includes the observatories, data management, core instruments, and technical development. Operations and maintenance, science funding, instrumentation, mobile platforms, and education/outreach are supported and funded through the ORION Program by the NSF Division of Ocean Sciences.

(IRIS). The most recent report, released almost contemporaneously with this science plan, is based on a major ORION community workshop held in January 2004 and attended by several hundred oceanographers, Earth scientists, and science educators (Schofield and Tivey, 2005). This report is broadly interdisciplinary and advocates an aggressive effort to create a multi-scale global observatory to address a wide range of questions in the Earth and ocean sciences.

Ocean Observatory Concept

An ocean observatory is infrastructure located at a fixed site in the ocean that facilitates spatial sampling from nanometer to megameter scales and temporal sampling from microseconds to decades. While collecting time series observations and samples at a single site, an ocean observatory may also support acoustic sensors and mobile platforms, such as AUVs, gliders, and profiling floats that can sample a large volume of the surrounding ocean.

At the highest level, the research-driven OOI will allow users or teams of users to develop a compatible ocean sensor, plug the instrument into the system, and automatically receive power and an Internet connection for data return and remote instrument control. The observatory will be sustained with operations extending for years or decades even in remote, hostile environments. Data will be returned from the sensor to the user's desktop in near real time with latencies that seldom exceed a few seconds from virtually anywhere in the world's ocean. The user in turn will be able to use OOI network services to control their instrument, for example, the rate at which data are sampled or the pan and tilt angles of a remote HDTV stereo camera. Scientific workflow methodologies will be used to integrate real-time data into models with no human intervention. Individual scientists or users will be able to construct their own private, virtual observatories for specific studies. The observatory will be adaptable so that as scientific questions and technologies change, the observatory itself can be readily adapted, for example, by changing or adding sensors or modifying the sensor software and system middleware.

The OOI will necessarily be interdisciplinary—several disciplines will be using the same infrastructure simultaneously to make measurements while disparate measurements at the same site will be sharing a common location and sampling regime, challenging scientists to examine correlations among disciplinary observations. Emergent phenomena, characteristic of non-linear interactions among Earth subsystems will be more readily observed. The educational opportunities of ocean observatories are enormous—the ocean is exotic, fascinating, and important to humankind. Real-time data, and high-speed interactive control of ocean observatories, will open entirely new opportunities for students and the general public to learn about the ocean and how it affects the planet on which we live.

Elements of the OOI

The OOI has three principal elements: (1) several deep-sea observatories based around a system of moored buoys; (2) a regional cabled observatory in the Northeast Pacific Ocean consisting of more than ten interconnected sites on the seafloor that span several geological and oceanographic features and processes; and (3) an expanded network of coastal observatories that use moored buoys and seafloor cables. Although comprised of these three different elements, the OOI is intended to function as an integrated whole linked by a common instrument, infrastructure, and information management system.

Global Component

The global component of the OOI will support the installation of a comprehensive network of time-series sites at about a dozen locations distributed around the world's oceans using advanced buoy technology. Each site will support a wide range of interdisciplinary measurements from the air-sea interface to the deep seafloor, with mobile platforms and *in situ* sensors for large-scale remote sensing. Given the paucity of observations in all fields of oceanography in the Southern Ocean and other high-latitude locations, installations in these environments will be a high priority. Figure 2.2 illustrates the planned scope

of the global observatory component of the OOI. This research-driven global observatory network will expand and complement the operational observing systems operated by NOAA, including the TOGA-TAO array in the equatorial Pacific and DART (tsunami warning) buoys.

The technical challenges of occupying many of these remote sites for years or decades will be substantial (see Chapter 4). Several different buoy/mooring designs may be employed. A spar buoy mooring design with high-end power (0.5 kW) and communications to the seafloor through an electro-optical cable between the buoy and a seafloor junction box is illustrated in Figure 2.3. This 40-m buoy, which provides great stability in high seas and is suitable for deployment in remote high-latitude locations, is moored to the seafloor through three anchor lines. The buoy communicates to shore via a geostationary C-Band satellite at rates as high as 1Mbps and uses the Global Positioning System (GPS) for timing and location to geodetic accuracy (error < 1 cm). A less expensive relocatable buoy with substantially lower data rates

and acoustic telemetry to independent seafloor or water column sensors will be used in less-demanding circumstances. The types of data collected by these systems will include meteorological, air-sea flux, ocean properties, acoustic thermometry, seismic, geodetic, tsunami, and other data.

Regional Cabled Observatory

The OOI will install the first multi-node, regional-scale cabled observatory. At the RECONN workshop in Fall 2003 (Purdy and Karl, 2004), the ocean science community chose the Northeast Pacific Ocean as the location for the first regional cabled observatory. Cross-cutting science themes that bridge the scales between global and coastal include: (1) observations of the dynamics of the oceanic lithosphere along tectonic plate boundaries, (2) temporal sampling of the fluids and microbial life forms circulating in the hydrothermal oceanic crust and seafloor, and (3) turbulent mixing and biophysical interactions at full-depth water-column sites in coastal and

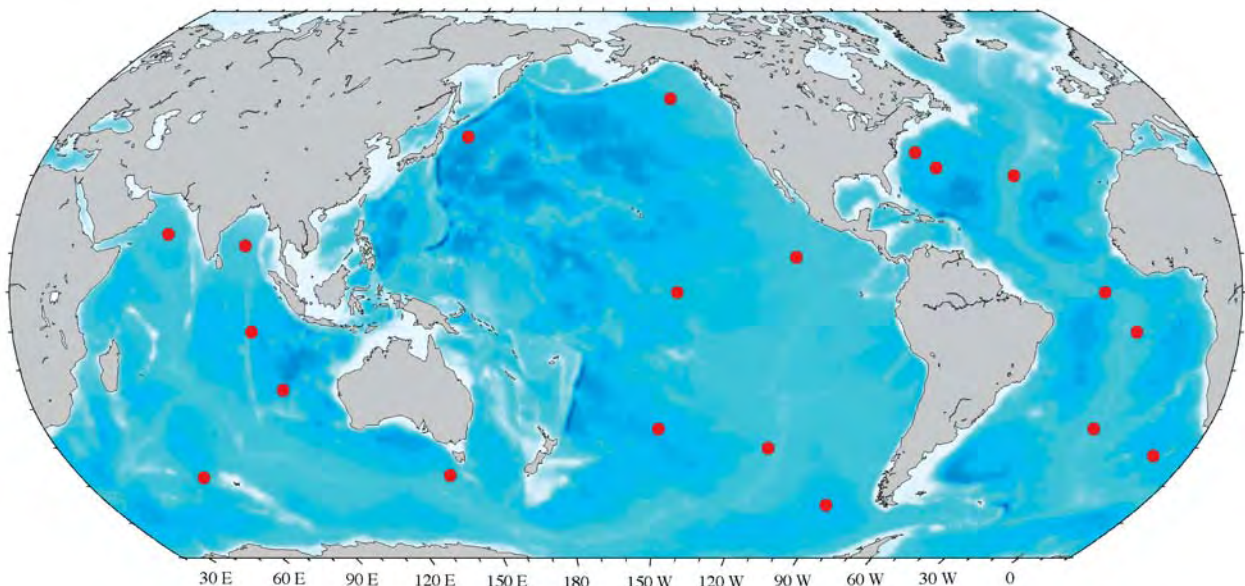


Figure 2.2. A notional map of the location of moored buoy observatories (red dots) comprising OOI's global component. Figure from National Research Council (2003).

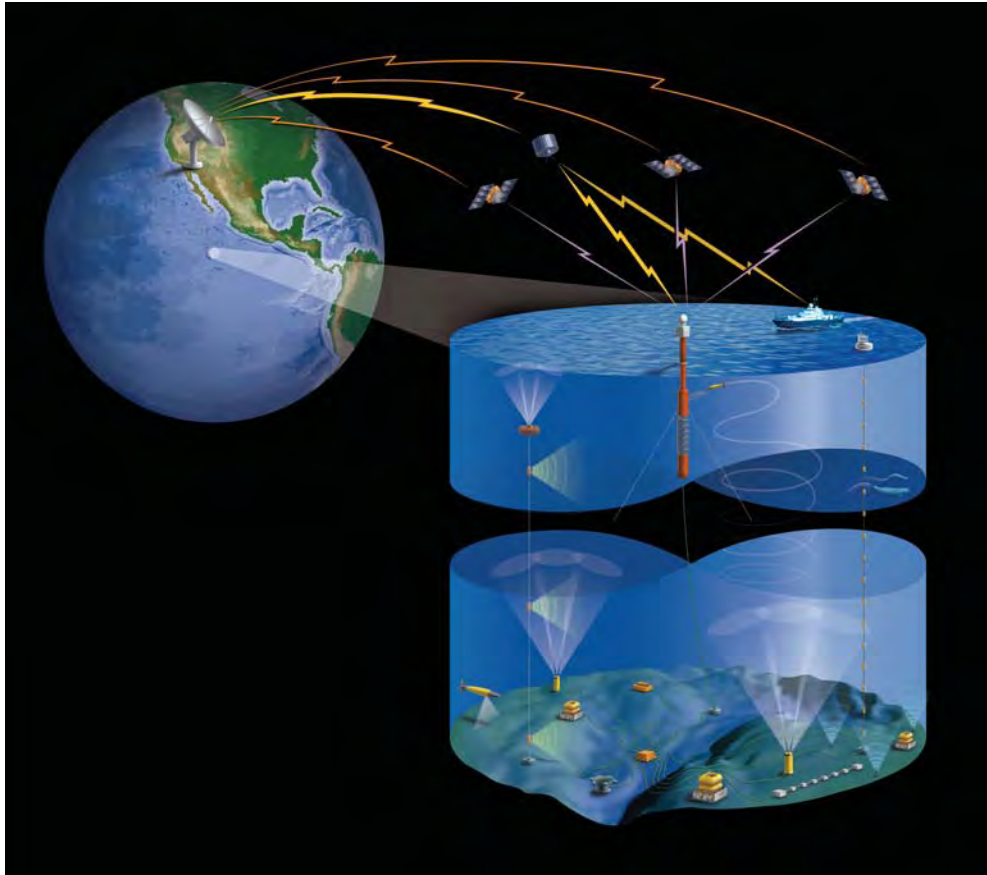


Figure 2.3. An OOI global observatory comprising a 40-m spar buoy, tri-moored anchor to the seafloor, and an electro-optical cable to a seafloor junction box. The junction box serves power and communications to a variety of sub-seafloor, seafloor, and ocean-column instruments. The buoy provides power to the seafloor from batteries and diesel generators and communications to a geostationary satellite. The GPS satellites are used for detailed geodetic measurements. Figure courtesy of John Orcutt, Scripps Institution of Oceanography.

shelf-slope settings. A regional cabled observatory in this area will build upon the pioneering work over the past two decades of the NOAA VENTS program (including the NeMO observatory at Axial Seamount and the Northeast Pacific SOSUS array).

The proposed NEPTUNE observatory is a model for a regional cabled observatory in this area (Figure 2.4). The planning for this observatory is being done in partnership with NEPTUNE Canada and comprises seafloor electro-optical cabling for power and communications, landfalls at two sites, scientific nodes supporting instrumentation, and coverage that includes the entire Juan de Fuca tectonic plate. A typical installation at Axial Seamount in the Northeast Pacific Ocean is depicted schematically in Fig-

ure 2.5. The local fiber optic Ethernet with transfer rates of 10-100 Gbps (four to five orders of magnitude higher than the moorings described above) and tens of kilowatts of power are integrated into the network in Figure 2.4. Instruments on (or below) the seafloor or extending up into the water column on sub-surface moorings are connected to the system at a seafloor junction box. Instruments are similar to those in Figure 2.3 although with the greater power and bandwidth provided by a cabled observatory, it would be possible, for example, to deliver HDTV in near-real-time 7/24/365. The junction box is functionally identical to the one used with moorings—instruments and standards will be designed to allow scientists and engineers to use their instruments largely independently of the local infrastructure (cabled or moored).

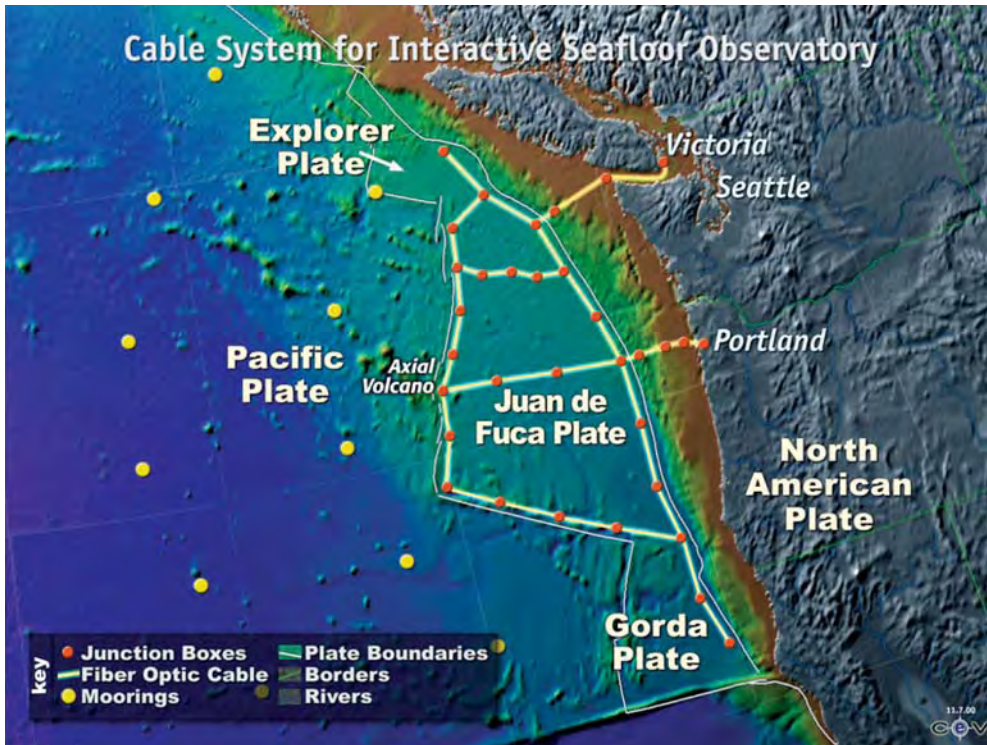


Figure 2.4. A potential regional observatory installation in the Northeast Pacific Ocean proposed by the NEPTUNE Project, including seafloor fiber optical and electrical cabling and scientific nodes. Image provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and the Center for Environmental Visualization.

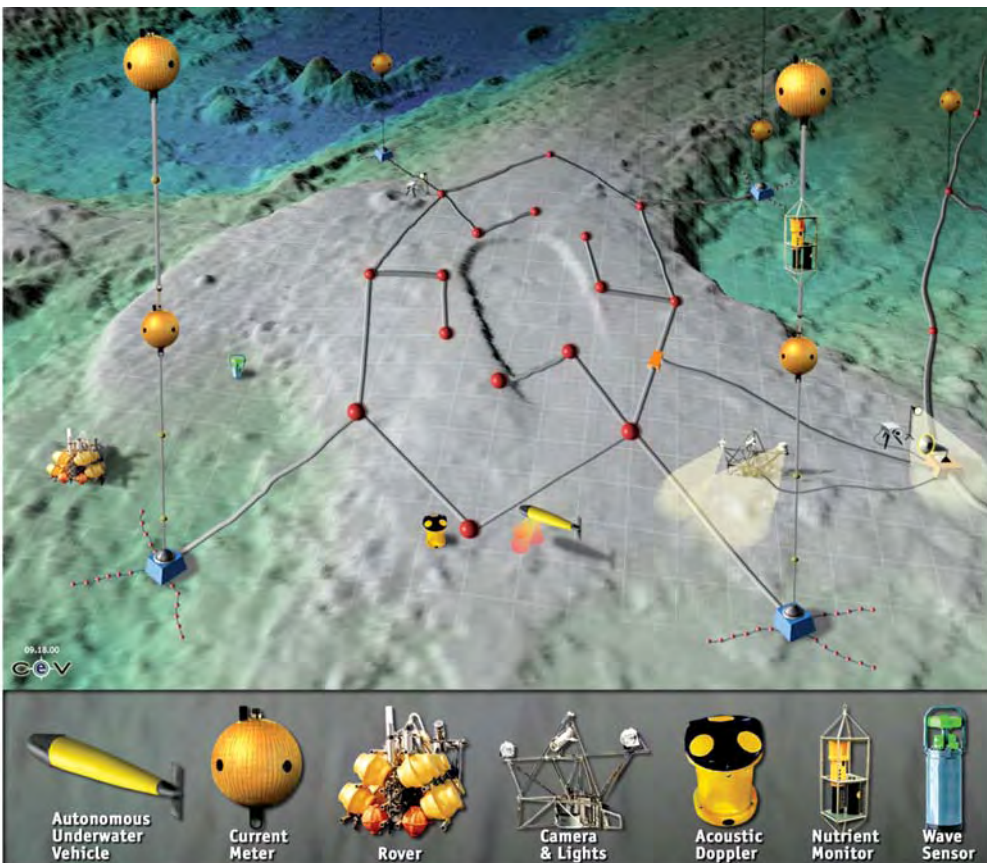


Figure 2.5. A generic experimental network draped over Axial volcano and is based on the National Oceanic and Atmospheric Administration/Pacific Environmental Laboratory's New Millennium Observatory (NeMO). The network will provide real-time command-and control capabilities to shore-based users via the Internet. Autonomous underwater vehicles will reside at depth, recharge at nodes, and respond to events such as submarine volcanic eruptions. This image is representative of the kinds of installations that will ultimately be located at each of the experimental sites (see Figure 2.4). Image provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and the Center for Environmental Visualization.

The Northeast Pacific regional cabled observatory will collect water column physical, chemical, and biological data as well as seafloor seismic, geodetic, electromagnetic, video, vent temperature and flux, and other data.

Coastal Observatories

The challenge of resolving the wide spectrum of temporal and spatial variability that characterizes coastal processes will require both advanced cabled and mooring-based observatories. Because environmental characteristics and the mix of controlling processes vary regionally, coastal observatories must be distributed among the major ecosystems of the United States while the resolution of sub-regional processes require more densely spaced measurement locations. Coastal observatories, therefore, will consist of two components; widely

distributed, long-term observatories (arrays of Endurance lines) supplemented with relocatable clusters of moorings (Pioneer arrays) (Figure 2.6).

The Endurance array is a long-term, interactive system comprised of moored or cabled observatories within key coastal environments that provide the infrastructure to examine infrequent, short-term episodic events, long-term trends, and the large-scale (thousands of kilometers) connectivity of coastal systems. These assets could be deployed as cross-shelf lines or installed at isolated locations, depending on the scientific objectives. While moorings may often be used for the Endurance array sites, more capable cabled systems will sometimes be preferred for both scientific and economic reasons. The power and bandwidth of the Endurance array mirror those of the global moorings and regional cabled observatory, and will greatly expand observing capabilities in the coastal ocean. They will also provide easily accessible test beds for the development of observing technology for use in the more remote locations. These systems may be augmented as needed by shore-based radars to map surface currents, and mobile platforms such as AUVs or gliders to provide broader spatial sampling and observations.

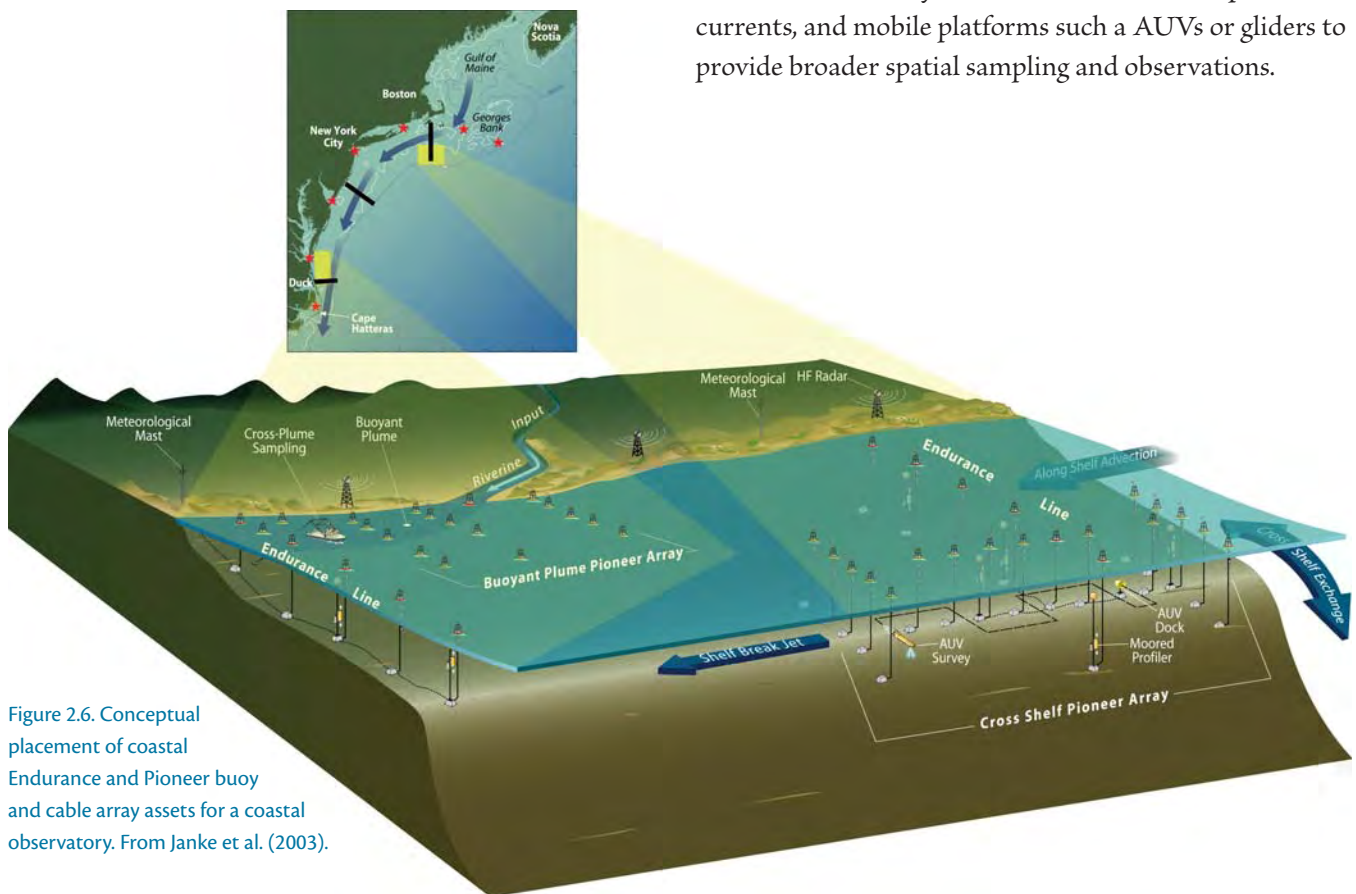


Figure 2.6. Conceptual placement of coastal Endurance and Pioneer buoy and cable array assets for a coastal observatory. From Janke et al. (2003).

Pioneer arrays are groups of autonomous, interactive moorings capable of providing real-time data integrated with land-based, high-resolution surface current radars and other remotely sensed data streams. A Pioneer array is a relocatable asset, deployable over time periods appropriate to the scientific questions at hand, perhaps for 1-7 years. These arrays will collect high-resolution, synoptic measurements spanning tens to hundreds of kilometers to advance understanding of sub-regional processes.

Why Now?

There are three compelling arguments for why it is essential that the OOI move forward now to establish the next-generation, research-driven ocean observatories described above.

1. We must maintain the leadership role of the United States in ocean and environmental observing systems. Other nations (Japan, Europe, Canada) have made, or are planning to make, major investments in ocean observing systems in the next few years. If the U.S. research community does not have access to these same tools it will not be able to pursue the most exciting and important questions in marine science.
2. The President's Commission on Ocean Policy has clearly identified many areas in which the oceans are in crisis, and it is essential that we act now to begin to address these issues. Improved understanding of all of these issues—the impact of pollution on coastal systems, managing of the ocean's living resources, improving earthquake and tsunami hazard assessment, and others—will benefit from the new knowledge of ocean processes and observing technology that the OOI will develop.
3. We must build the OOI network now in order to leverage various research-driven and operational observing systems being developed in the United States and in other nations by coordinating ship time (for observatory installation, servicing and maintenance), data management, and education and outreach efforts.

Intellectually this shift from expeditionary to observatory-based research is driven by long-standing scientific problems and by new questions and hypotheses across a broad range of Earth and ocean sciences that cannot be addressed using more conventional approaches. Technically, this paradigm shift is feasible now because of major advances in several different fields including evolving sensor development (encouraging *in situ* measurements of an ever growing suite of physical, chemical, and biological properties); advances in communications technology (allowing two-way data communication via satellite or high bandwidth fiber optic cable from anywhere in the world's oceans to a scientist's desktop) and power delivery systems (allowing instruments with much higher power requirements to be used routinely in marine experiments); developments in cyberinfrastructure (providing the capability to manage large volumes of data in real time or near real time and to control remote sensor networks interactively), and in the speed and miniaturization of computers, which will allow eventual deployment of very intelligent nodes on the network.

The OOI builds on the legacy of large oceanographic re-search programs that encouraged multidisciplinary approaches and collaborative investigations during the past 15 years (e.g., WOCE, JGOFS, RIDGE, ODP, GLOBEC, IRONEX, CLIVAR, CoOP), provided training in interdisciplinary science, and developed hypotheses and raised questions about ocean systems that demanded a new investigative approach. The success and experience gained with pioneering observatory projects in both the coastal (e.g., LEO-15, MVCO) and open (e.g., HOT/BATS, TOGA-TAO, NeMO) ocean, as well as engineering knowledge gained in various pilot experiments and testbeds (e.g., MARS [United States], VENUS [Canada], HighSeasNet), have laid the groundwork for the major investment in this new technology that is now being proposed.

CHAPTER 3. RESEARCH THEMES AND OPPORTUNITIES



By providing a permanent observational presence in the ocean capable of resolving short-term events, documenting synchronicity of properties across broad spatial scales, and resolving long-term change, the ORION Program, and the OOI infrastructure in particular, will afford numerous opportunities to advance scientific understanding and explore the marine realm. Opportunities span all disciplines, including such diverse issues as identifying the natural products and production enzyme systems of ma-

rine ecosystems, advancing understanding of Earth structure and earthquakes, tracking the migration patterns of whales, quantifying impacts and feedbacks of climate change on the oceans, and improving predictions of coastal inundation from storms and tectonic events. In the accompanying sections, we highlight a few examples of the advances that are anticipated from the development and implementation of research-driven ocean observatories.

3.1. Climate Variability, Ocean Food Webs, and Biogeochemical Cycles

Our understanding of global climate dynamics is limited by our knowledge of the interactions among the ocean, atmosphere, and land. The thermal inertia of the oceans ensures that many of the cycles occur over longer time scales than can be effectively sampled using traditional ship-based research techniques. Furthermore, these interactions are affected by the numerous modes of climate variability (e.g., the El Niño Southern Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation) that alter the transport of heat, salt, carbon, nutrients, and biological productivity and diversity. Superimposed on these low-frequency cycles is significant interannual variability due to high-frequency variability in the climate system. The short duration of ship-based expeditions has hampered efforts to study this high-frequency variation. Until understanding of these 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 cycles requires high-frequency, sustained spatial time-series data from coastal, regional, and global observatories coupled to physical-chemical-biological numerical models.

Human activity has altered Earth's biogeochemical cycles, which in turn has modified the global ocean-climate cycle. For example, industrialization has resulted in an increase in atmospheric CO_2 , which alters the heat budget of the atmosphere and thus influences climate. The oceans serve as a sink for increased atmospheric CO_2 , but the magnitude, timing, and variation of CO_2 uptake in different regions of the oceans are not well constrained. This is especially true for continental shelves. Sequestration of atmospheric CO_2 is influenced by ocean temperature, circulation, and biological productivity, which are, in turn, regulated by global climate.

NSF's role in climate studies is to develop a better understanding of the climate system to better constrain various climate-change scenarios. This will require the collection of data in critical, often inhospitable, geographic locations for sustained periods of time. The challenge of collecting continuous time-series data in these areas is formidable. Physical and biogeochemical properties are highly variable and linked over a wide range of spatial and temporal scales (meters to thousands of kilometers, hours to decades), and cannot be adequately measured or sampled using traditional approaches (Figure 3.1.1). Satellites provide a synoptic, global perspective on the ocean, but are limited to measuring properties near the ocean surface. Advancing our knowledge about the role of the oceans in climate variability requires observational platforms for *in situ* measurements that can determine the three-dimensional complexity and non-linearity of ocean processes.

Examples of Key Scientific Questions

What is ocean's role in storing anthropogenic carbon?

The ocean contains greater than 50 times more CO₂ than the atmosphere. Thus, a small perturbation of the ocean carbon cycle can result in a substantial change in the atmospheric CO₂ concentration. For 420,000 years before the Industrial Revolution, CO₂ concentrations in the atmosphere fluctuated between 190 and 280 ppm. Since the Industrial Revolution, atmospheric CO₂ levels have been rising and now stand at about 380 ppm. Only about 50% of the CO₂ that has been added to the atmosphere via fossil-fuel burning and industrial activity resides there. This means that the other half has gone into the ocean or has been incorporated into the biosphere on land. Understanding the role of the ocean in the uptake of anthropogenic CO₂ is critical to predicting the effect of CO₂ emissions on climate.

Exchange of CO₂ between the atmosphere and the oceans is mediated by two phenomena. The "solubility pump" is driven by air-sea gas exchange and inorganic chemistry in the oceans. CO₂ distribution and solubility (which depend

strongly on temperature) are very patchy, resulting in heterogeneous air-sea flux. The magnitude and direction (source/sink) of the flux between the atmosphere and the ocean is a function of the partial pressure of CO₂ ($p\text{CO}_2$) at the air-sea interface, sea surface temperature, wind speed, and surface roughness. A critical element needed to address these processes is an improved understanding of the mechanisms of air-sea gas exchange and mixing between the surface ocean and the top of the thermocline.

The second mechanism by which CO₂ exchanges with the ocean is via biological carbon fixation ("the biological pump"), which produces particulate and dissolved organic carbon. Organic matter is reoxidized to inorganic carbon through respiratory mineralization upon sinking into the ocean's interior (Figure 3.1.2) More efficient operation of the biological pump may have caused lower atmospheric CO₂ levels during the last glacial maximum (200 ppm as opposed to the pre-industrial 280 ppm). Organic matter is reoxidized to inorganic carbon by respiration upon sinking or mixing into the ocean interior, where the water is sequestered from the atmosphere for hundreds to thousands of years. This process is unlike terrestrial ecosystems where substantial amounts of carbon are stored directly as biomass (mostly trees) and organic matter in soils. Oceanic photosynthetic biomass amounts to < 0.5% of the terrestrial biomass, but the uptake of organic carbon in marine ecosystems approaches 50% of the global total. Hence, oceanic ecosystems have relatively high carbon turnover rates in the ocean's surface layer. Depending on ecosystem sensitivity, climate change may alter these high turnover rates.

Despite its importance, our understanding of the biological pump is surprisingly limited due, in part, to recent observations that suggest that episodic blooms, which are not well resolved using traditional techniques, may dominate the flux of carbon to the deep sea (Figure 3.1.3). Ecosystem structure and the interactions between producers and consumers affect the efficiency and amount of carbon exported from the surface waters to the ocean's deep interior; however these interactions may change

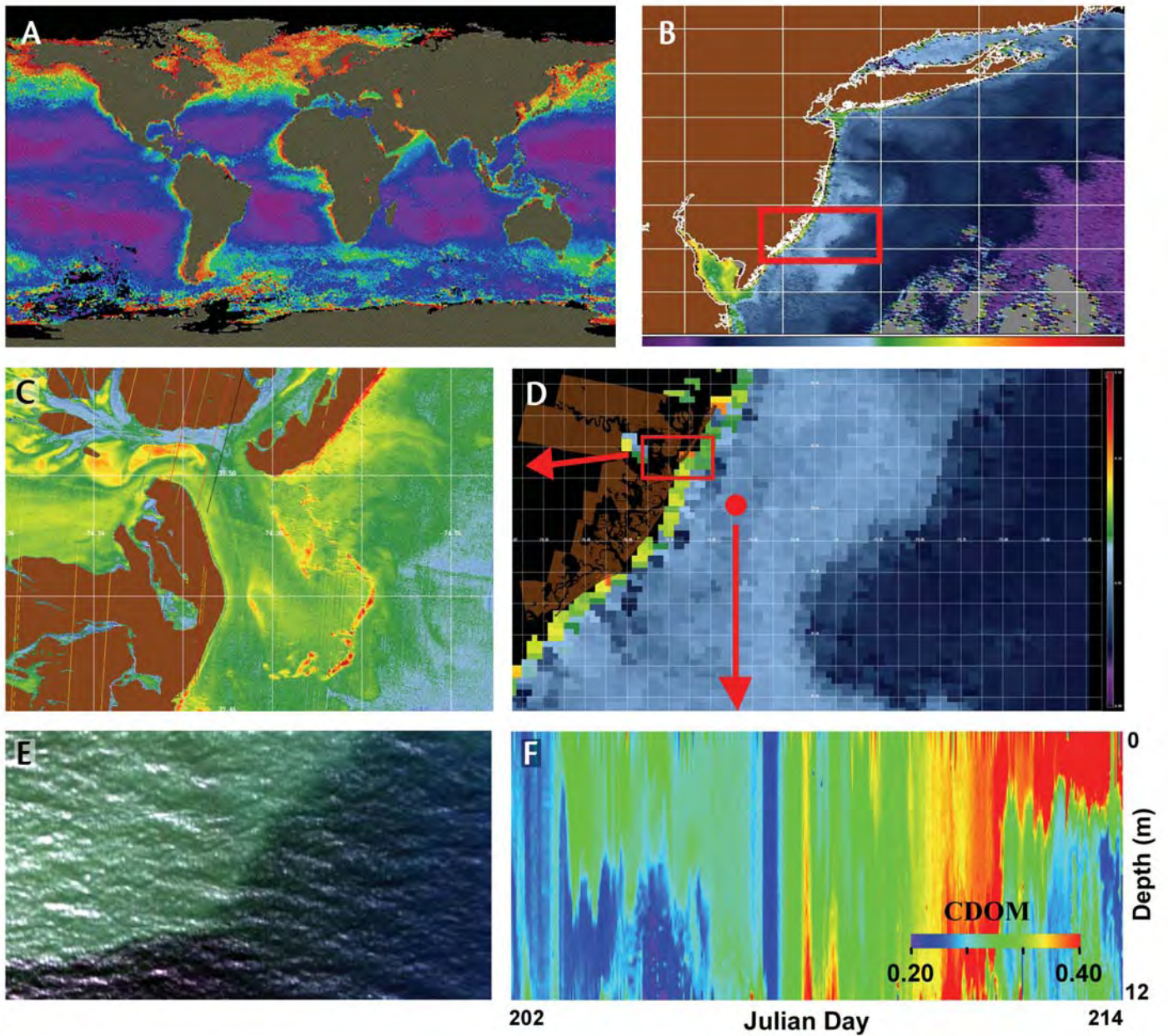


Figure 3.1.1. The temporal and spatial variability in ocean plant productivity. (A) An annual global chlorophyll a map illustrating areas of the ocean associated with high biological activity (<http://seawifs.gsfc.nasa.gov/SEAWIFS.html>). (B) Blow-up for Northeast United States in summer 2001 showing optical backscattering which is proportional to particle concentrations. (C) An enlarged section of panel B focusing on the backscattering signal derived from the SeaWiFS observations; the satellite's 1-km pixel is clearly visible and illustrates the features in the coastal ocean that are poorly resolved. (D) An enlargement from panel C showing backscatter measured by aircraft. Note what is missed with the standard 1-km pixels in the satellite imagery. (E) A visible image viewed by aircraft, with resolution on the order of tens of meters, showing the dramatic color change associated with crossing an upwelling front in the Mid-Atlantic Bight. The visible "greening" of the water is associated with enhanced blue light absorption associated with marine phytoplankton. (F) Time series of colored dissolved organic matter (CDOM) absorption, estimated from inverting bulk absorption measured with an ac-9 mounted on the Long-Term Ecosystem Observatory (LEO) electro-optic fiber optic cabled seafloor node (Oliver et al., 2004). Rapid changes in CDOM concentration are associated with the passage of storms and Hudson River water. Figure from Schofield et al. (2004).

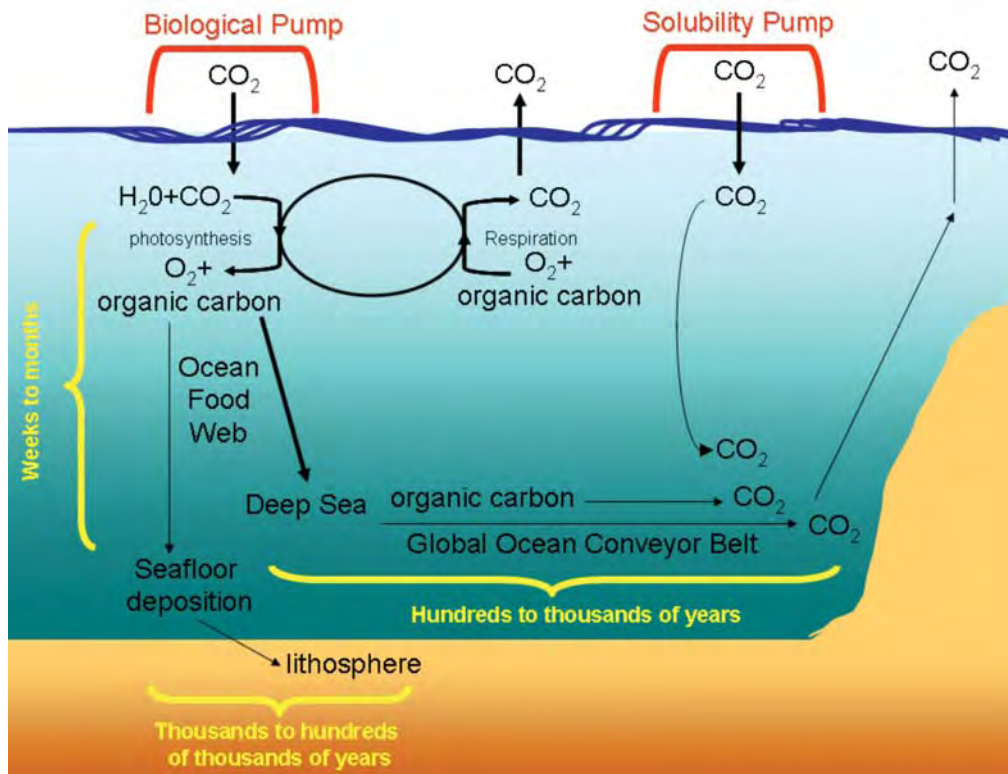


Figure 3.1.2. The biological and solubility pumps and their role in transporting atmospheric carbon to the deep sea. Figure courtesy of Oscar Schofield, Rutgers University.

with higher $p\text{CO}_2$ levels. Increasing ocean CO_2 concentrations are acting to decrease ocean pH (making the ocean more acidic), which will affect biological calcification rates, and thus coral reefs as well as coccolithophorid populations, which are major contributors to the formation of calcium carbonate in the oceans. Atmospheric warming, particularly in the Arctic, already has diminished polar sea ice, which regulates productivity in high-latitude marine ecosystems.

Understanding how interactions between biology and geochemistry drive organic matter flux and remineralization will be a major challenge in the coming decade. Many of the critical processes can be observed either directly or indirectly with available satellite and *in situ* measuring technology; however, these assets are rarely deployed for long-time-series studies. Data collected at high sampling rates are required to quantify the importance of episodic events. Multidecadal time-series data are needed to

quantify subtle changes in location and timing of biologically controlled carbon sinks and sources. A distributed network of observatories capable of providing sufficient power to support physical and biogeochemical sensing systems are needed to address these issues.

What is the magnitude and cause of recent sea-level rise?

At the end of the last ice age, global sea level was 125 m lower than modern levels, but by 2000 BC sea level had stabilized near present levels. Global satellite altimetry shows a notably larger than average sea-level rise in the last decade of the 20th century compared to the previous 4000 years. As sea level is one quintessential metric for climate change, this observation, coupled with published reports of melting polar ice caps and mountain glaciers, has sparked scientific and public debate regarding the underlying cause of the observed sea-level rise.

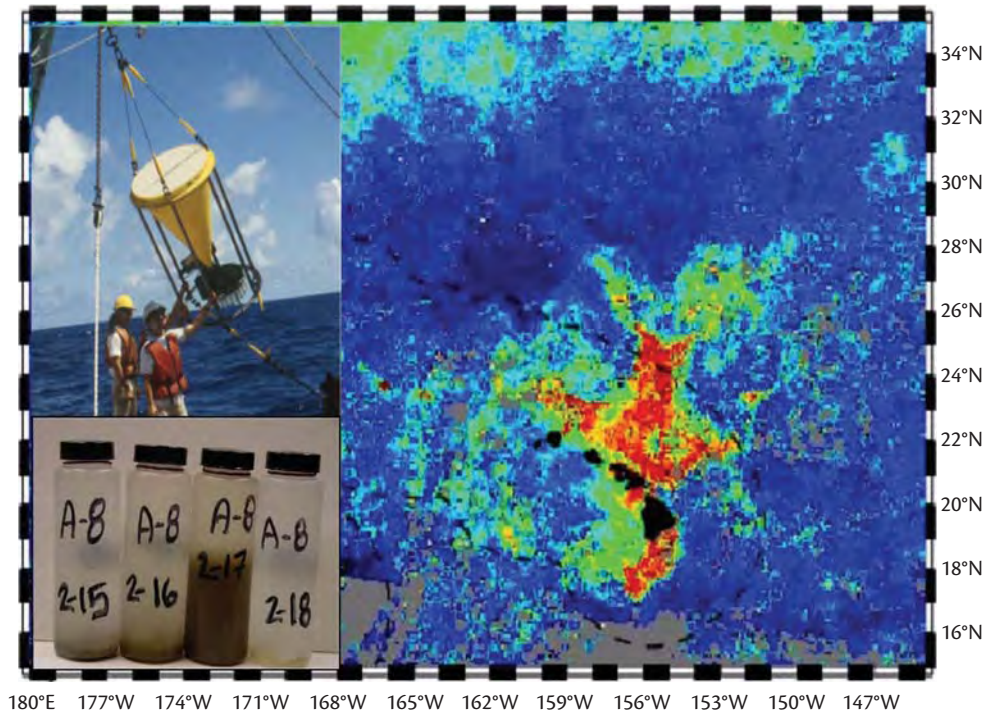
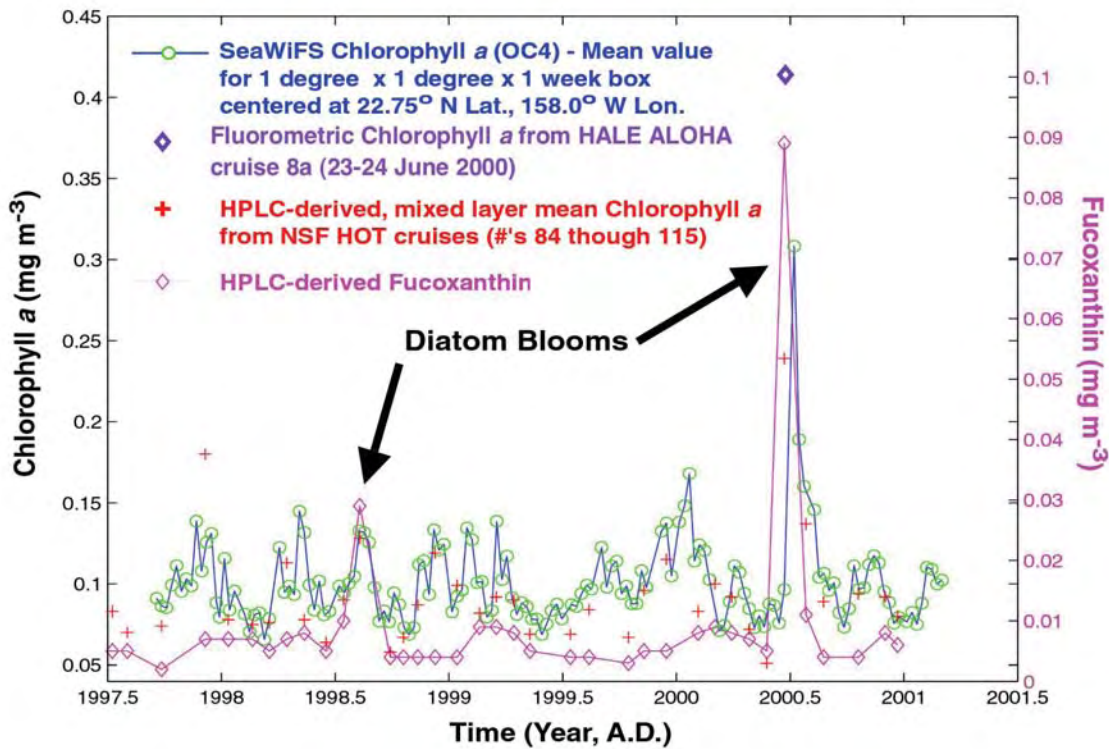


Figure 3.1.3. Potential sequestration of carbon from the atmosphere into the ocean is strongly dependent on new production and the corresponding export flux of organic matter from surface waters to the deep sea. New production events occur over seasonal and shorter time scales. These shorter-time-scale responses lead to significant export flux. Results collected at the Hawaii Ocean Time Series site illustrate that a single diatom bloom can account for the majority of exported material over several years. Sediment traps have provided the only reliable means to quantify the export flux; however, these approaches often have a limited spatial footprint. Satellites provide wonderful spatial coverage, but often miss subsurface phytoplankton blooms. ORION would provide an array of fixed and mobile assets that could be used bridge this gap and could be used to measure new production and the resulting export flux. Figure courtesy of R.R. Bidigare and D.M. Karl, University of Hawaii. The Hawaii Ocean Time Series (HOT) team is also gratefully acknowledged.

Photosynthetic Pigment Time Series for Station Aloha Region

HOT *in situ* and SeaWiFS satellite-derived data



Traditionally, estimates of thermal expansion of seawater due to warming and freshwater exports from continents were believed to account for the majority of the observed sea-level rise. However, these steric effects were shown to be insufficient (Munk, 2002). Thus, traditional eustatic sources for sea level rise are probably more important than initially believed. However, current estimates of both steric and eustatic effects cannot account for present estimates of sea-level rise, which suggests that either current sea-level-rise estimates are incorrect or that estimates of ocean heat storage effects need to be revised. Given these discrepancies, resolving the respective contributions of ocean warming and ice melting to sea-level rise is a fundamental research question. Expanding the global observation network of water-column temperature and salinity at open ocean sites, especially at high latitudes, together with basin-scale acoustic thermometry measurements from observatory sites, would better constrain explanations and predictions of global sea-level rise.

What is the importance of low-frequency climate cycles versus longer-term global change for ocean food webs?

Currently, the largest documented modern climate anomalies are associated with ENSO events during which water temperatures may rise as much as 2-3°C in the eastern Pacific. These measurements, made by NOAA's TOGA-TAO array in the tropical Pacific, have demonstrated the need for a sustained ocean observing system to understand these decadal climate oscillations. The interannual effects of ENSO on marine communities are beginning to be documented. For instance, along the west coast of the United States, ENSO events led to decreased nutrient availability, reduced production in phytoplankton and zooplankton, and increased mortality of their predators (e.g., sea birds and seals). Salmon migration routes in British Columbia have been linked to environmental changes due to ENSO events. Ocean biogeographical boundaries also shifted during these events, with strong transport from the south displacing and altering food webs and leading to variations in the distribution of pelagic fishes. Furthermore, ENSO events are associated with globally significant outbreaks of infectious

diseases such as cholera. The warmer water enhances the growth of a pathogenic microorganism, *Vibrio cholerae*, which lives in marine zooplankton (i.e., copepods).

Compelling evidence exists in the North Pacific for a basin-scale Pacific Decadal Oscillation (PDO) where interdecadal shifts in the physical environment and the marine ecosystem are linked to large-scale shifts in atmospheric processes. Effects of the PDO are manifest in many regions of the North Pacific Ocean. Limited time-series data reveal that chlorophyll doubled in the subtropical North Pacific after the mid-1970s, with similar changes in zooplankton and pelagic fish biomass in the 1980s. Off the west coast of the United States and Canada, zooplankton community composition and biomass changed during the late 1980s and again in the late 1990s. The abundance of northern species decreased, while warm-water species increased, in association with increases in ocean heat content and poleward coastal transport. Salmon returns to the Columbia River increased during the negative or cool PDO phase, presumably due to the increase in availability of northern lipid-rich zooplankton (Figure 3.1.4).

The climate of the North Atlantic also has shifted during the last 40 years, as indicated by the North Atlantic Oscillation (NAO) index. The NAO index changed from generally negative to largely positive values, concomitant with changes in ocean circulation and declines in the copepod *Calanus finmarchicus* and, as a consequence, declines in Atlantic cod stocks. While time-series data have permitted insights into the effects of large-scale forcing on ocean ecosystems, new research efforts are needed to improve understanding of a dynamic and changing ocean environment and the linkages among ocean physics, chemistry, and dynamic marine populations at relevant temporal and spatial scales.

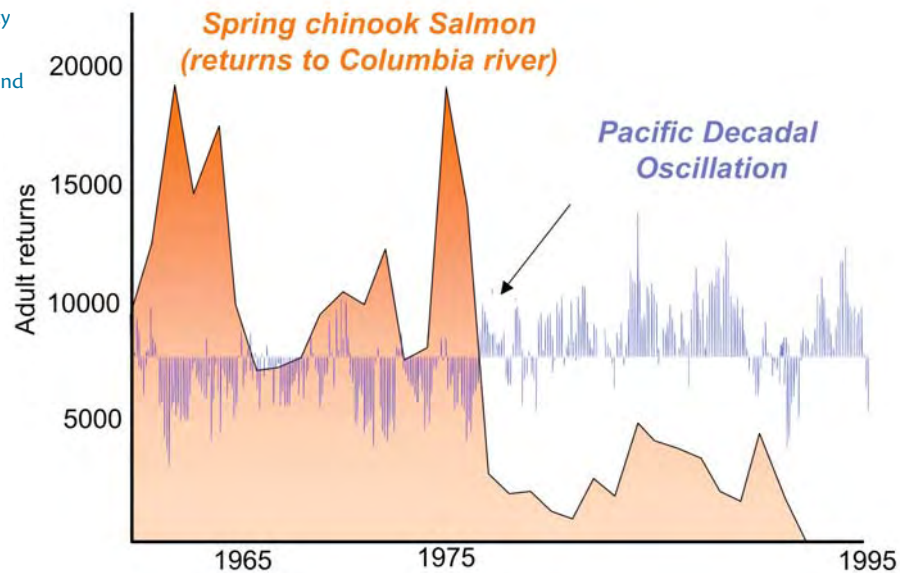
Role of Ocean Observatories

New mooring, mobile platform, and instrumentation technology, in addition to wireless and fiber optic communications, now make it possible to effectively deploy

Figure 3.1.4. Correlation between the presence of spring Chinook salmon in the Columbia River and the Pacific Decadal Oscillation. Salmon returning to the Columbia River increased during negative or cool PDO phases, presumably due to the increase in availability of zooplankton on which they feed. Figure courtesy of Manuel Barange and the International GLOBEC Office.



Regime Shift



and maintain unmanned observatories. These observatories will autonomously carry out diverse measurements over extended time periods, while providing much of their data to shore-based users via satellite or fiber optic cables in near real time. The OOI will provide the infrastructure for making measurements in the ocean and at the air-sea interface needed to quantify temporal variations in ocean physical, chemical, and biological properties at appropriate vertical and horizontal scales. Near-real-time telemetry of time-series data will allow adaptive sampling in response to episodic events (see Sidebar 3.1), which is necessary to detect non-linear interactions within the marine biosphere. Multi-decadal measurements are essential for determining how the oceans and the marine communities they harbor respond to large-scale atmospheric forcing and climate variability.

The OOI time-series sites will complement other components of a global climate observing system, including the Argo profiling float program and satellite altimetry missions. Fixed-point time-series are an essential element of a global observing system because they can resolve a wide range of temporal variability in the water column from the sea surface to the seafloor over time periods of decades or longer—something neither satellites nor profiling floats can do. Fixed-point time-series stations are also the only approach for resolving multidisciplinary variability and processes, including CO₂ uptake, biological productivity, and ocean-atmospheric fluxes. Furthermore, the OOI infrastructure will allow sustained measurements in remote ocean regions that are not easily accessible by traditional shipboard sampling, but appear to play a disproportionately large role in determining the global climate signal.

SIDEBAR 3.1. AIR-SEA EXCHANGE PROCESSES AND THE IMPORTANCE OF STORMS

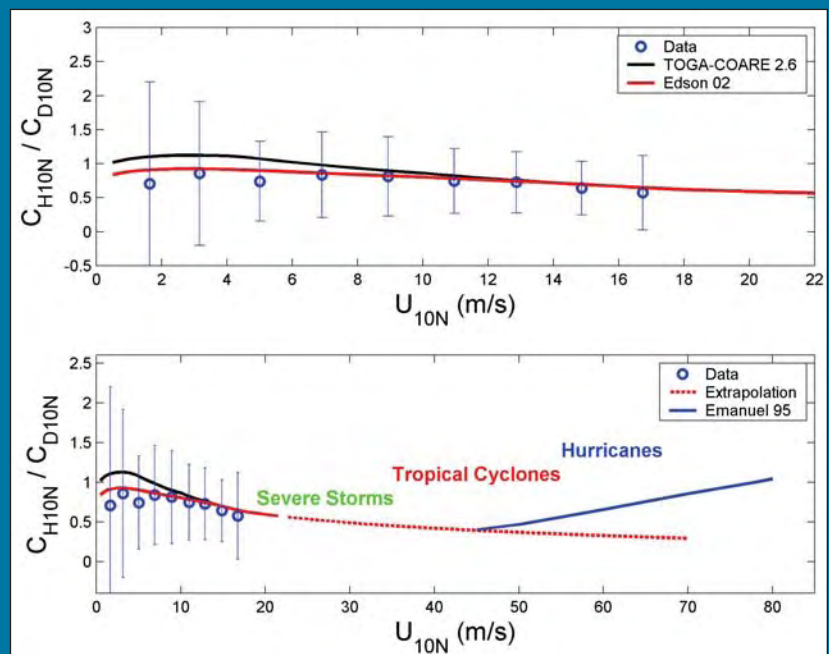
Contributed by James Edson, University of Connecticut

In the last few decades, substantial progress has been made in making direct measurements of air-sea momentum, mass, and heat exchange from ocean-going platforms due to improvements in our ability to remove motion contamination and flow-distortion effects. 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. However, decades of expeditionary measurements from research vessels have done little to advance understanding of heat, mass, and momentum fluxes at wind speeds above 20 m/s.

The figure shows the ratio of directly measured heat-exchange coefficients (the fuel for the atmosphere) to drag coefficients (the brakes on the atmosphere) from a decade of field observations in the 1990s. Although a few momentum flux measurements have been made at wind speeds above 20 m/s, this figure provides an honest representation of the state of the science, which shows no information about air-sea exchange in severe storms and no direct surface-layer measurements in tropical storms and hurricanes. This lack of data is a real impediment to forecasting storm intensity accurately. Numerical modelers have shown that extrapolation of current parameterizations (broken red line) does not allow hurricane formation due to too much drag and/or too little fuel exchange. These modelers have proposed parameterizations like those shown in blue.

Our inability to make these measurements at high wind speed is due to the harsh conditions encountered at sea, and research vessels not willingly entering into these regions due to safety concerns. Therefore, it is unlikely that our understanding of air-sea exchange at very high wind speeds ($U > 20$ m/s) can be significantly improved from

ship-based measurements. Additionally, high sea states, low visibility, corrosive spray, and otherwise dangerous low-level winds restrict aircraft operations to heights that are well above the region directly influenced by air-sea interactions. One solution is to make long-term, continuous, direct measurements of momentum, heat, and mass fluxes at both coastal and ocean observatories arranged along probable storm tracks or by deploying arrays in regions associated with high wind speeds, such as the Southern Ocean. The latest generation of sonic anemometers is capable of providing accurate estimates of momentum and buoyancy flux to wind speeds of 30 m/s. Some instruments are now available; however, rugged hygrometers and thermometers must be developed to handle the high winds and spray. Additionally, rugged, fast-response anemometers must be developed to survive extreme wind conditions encountered in hurricanes and typhoons. All of these developments will greatly increase our understanding of storms, their role in air-sea exchange, and their impact on the physics, chemistry, and biology of the oceans.



Relationship between the ratio of the 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. Note how few data exist for extreme storm events.

3.2. Coastal Ocean Dynamics and Ecosystems

Most human-ocean interactions occur in the coastal zone. Coastal waters exert a major influence on weather systems that impact the coastal regions, where more than 50% of the human population resides. Greater than 90% of the world's fish catch is harvested from coastal waters that also support major recreation and maritime industries. Marine-related hazards to human populations and property, such as coastal inundation due to hurricanes or tsunamis, are also greatest near coastlines. Transport across the coastal ocean exerts a dominant control on major global chemical cycles determining, for example, material exchange between the terrestrial and oceanic realms. 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 freshwater 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 (e.g., formation of hypoxia); recruitment of living marine resource organisms; benthic and water-column habitats; the invasion of harmful algal species; 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. Despite the importance of these processes, their formation, occurrence, and dynamics are not yet fully understood or quantified. In most cases, we have been unable to directly measure or

observe the controlling processes. Instead, we have had to resort to estimating the characteristics of these processes from resulting net distributions. In a few cases, isolated *in situ* instruments have captured individual transport events, but because these instruments were not interactive, remote samplers could not be triggered and measurement frequency could not be adjusted to optimize temporal resolution.

Making this task more difficult is the realization that relevant processes operate on a wide spectrum of spatial and temporal scales. An expedition or sampling protocol optimized for a particular temporal or spatial scale will miss or poorly resolve other scales. Cross-shelf transport may be localized at fronts or within specific filaments or jets, which may be guided by bottom topography or meander across the shelf. Water-column mixing and seafloor exchange may vary temporally in response to storms or internal waves. Coastal processes (e.g., sediment resuspension or fluid mud formation) may also have distinct thresholds, additionally complicating attempts to match forcing factors to resulting transports. Some inputs, such as groundwater discharge, may be influenced or controlled by inland processes such as rainfall events. Additionally, coastal characteristics and the relative mix of controlling processes vary regionally requiring measurements that are distributed amongst the major coastal ecosystem types. In general, short-term mooring deployments and expeditionary measurements have not provided observations over the breadth of scales required to resolve the dominant processes. Inferences from the comparisons of discrete observations accumulated over many years of study may be incorrect or misleading because of undocumented temporal trends in response to variations in climate or anthropogenic activities. A significant advancement in understanding coastal processes will require a continuous, distributed observational presence to detect episodic, short-term events and to resolve long-term trends.

Examples of Key Scientific Questions

What processes determine the transport of carbon, nutrients, planktonic organisms, and other materials within the coastal ocean ecosystem?

Critical to advancing understanding of coastal ocean systems is the need to quantify and elucidate the transport of materials and organisms across the margin (Figure 3.2.1). Biological production is supported by nutrients that may come from land near rivers or from the atmo-

sphere, but more generally are supplied from nutrient-rich offshore ocean waters. Coastal environments may serve as a major trap or filter of terrestrial particulate materials, including contaminated particles, depending on the dynamics of current—seafloor interactions that control deposition and resuspension. Recent studies reveal that advection through permeable shelf sediments may greatly accelerate the exchange of nutrients and particulates between the seafloor and overlying waters. Groundwater exchanges are increasingly recognized as potentially important but the dynamics and control-

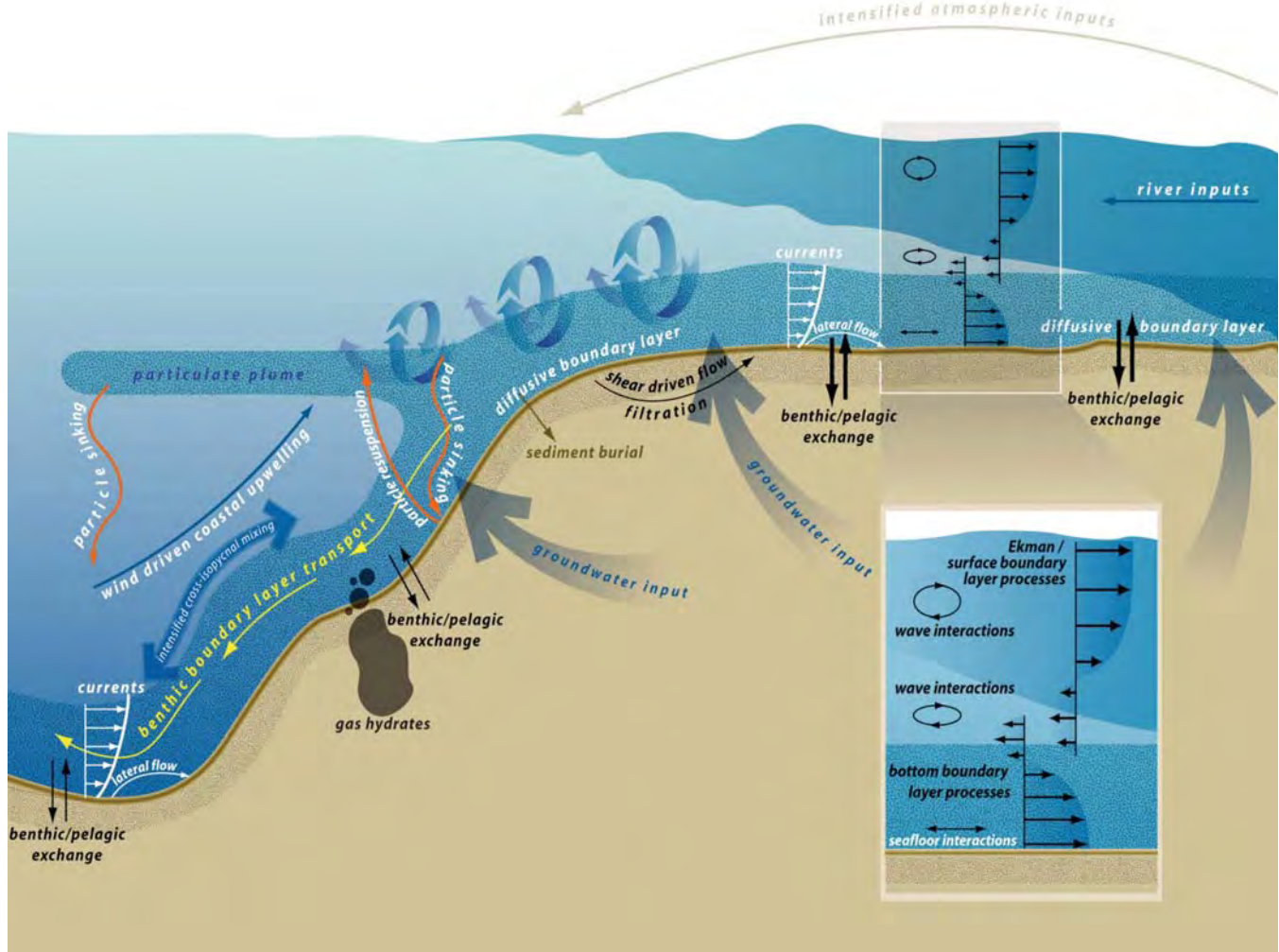


Figure 3.2.1. Selected processes that are intensified or unique to continental-margin ecosystems. Figure developed from CoOP's Coastal Benthic Exchange Dynamics (CBED) Workshop; designed by A. Boyette, Skidaway Institute of Oceanography.

ling external forces are largely unknown. Adding to the intellectual challenges is the mounting evidence that human activity is altering nutrient patterns and food-web structure and changes will likely increase in the future as population pressure intensifies and coastal regions are further developed. Consequently, studies of process interactions must be conducted under changing conditions.

Cross-shelf transport of larvae is a particularly important example. Many important coastal species include an offshore larval stage that must be transported to near-shore nursery grounds for successful growth to maturity. Improved understanding and management of coastal ecosystems depend on elucidation of the mechanisms and magnitude of this transport. Traditionally, studies of larval distributions have been investigated with regional ship-based surveys in which larvae are collected at predetermined sampling locations. This measured distribution is then interpreted in the context of coastal circulation to estimate larval transport. Recently, however, fine-scale, shoreward currents have been documented to be associated with fronts and other features that may dominate shoreward movement of larvae. Because these fine-scale currents are very narrow (often only a few kilometers in width) and their position and strength may shift over time, they are generally not resolved by more widely spaced, infrequent ship-based surveys. To better understand life-cycle characteristics of coastal species and to effectively manage coastal ecosystems, we must improve measurements and understanding of this critical exchange.

What conditions trigger the occurrence of harmful algal blooms and regime changes in the species composition of coastal ecosystems?

Although periodic changes in coastal ecosystem communities have been recognized for decades (e.g., sardine/anchovy shift that occurred on the U.S. west coast in the 1930s), the global extent, teleconnections and synchronicity are only now being appreciated. The last two decades have also been marked by a greater appreciation of the serious impacts of harmful algal blooms (HABs).

Although HABs were present long before human activities began to impact coastal ecosystems, a survey of affected regions and of economic losses and human poisonings throughout the world demonstrates that there has been a dramatic increase in the impact of HABs over the last few decades. These occurrences of toxic or harmful microalgae represent a significant and seemingly expanding threat to human health, fishery resources, and marine ecosystems throughout the world. While both natural and anthropogenic influences may be responsible for the dramatic expansion in HAB effects, it is likely that human activities are making the problems worse through increased nutrient inputs to coastal areas, transportation and discharge of ballast water, and other factors.

A great deal is known about HABs, but our ability to describe the factors controlling the dynamics of individual species is limited by critical gaps in understanding the physiological, behavioral, and morphological characteristics of the algae and how these interact with coastal oceanographic conditions. While their occurrence is generally readily apparent (Figure 3.2.2), the causal mechanisms (climate, anthropogenic nutrient inputs) are a subject of intense debate. The difficulty is to understand how slow-growing harmful algae can increase to sufficient numbers that their toxin levels can perturb the entire marine ecosystem (even though most other phytoplankton taxa grow at faster rates). Without mechanistic understanding, prediction of HAB occurrence can not happen and we can not target for study the conditions leading up to and triggering these events.

HABs are dynamic events resulting from a unique but poorly sampled set of physical, chemical, and biological forcings (Figure 3.2.3). By providing a permanent observational presence in coastal waters, the OOI will provide unique information about ocean conditions prior to the onset of HABs, direct sampling and biological studies of blooms in very early stages of development, and measurement of processes by which blooms are maintained and transported. This will lead to improved forecast models of nascent HABs, such as NOAA's forecast model for the Florida Shelf.



Figure 3.2.2. Cyanobacterial bloom in the Baltic Sea being traversed by a research vessel. Photo from GEOHAB (2001).

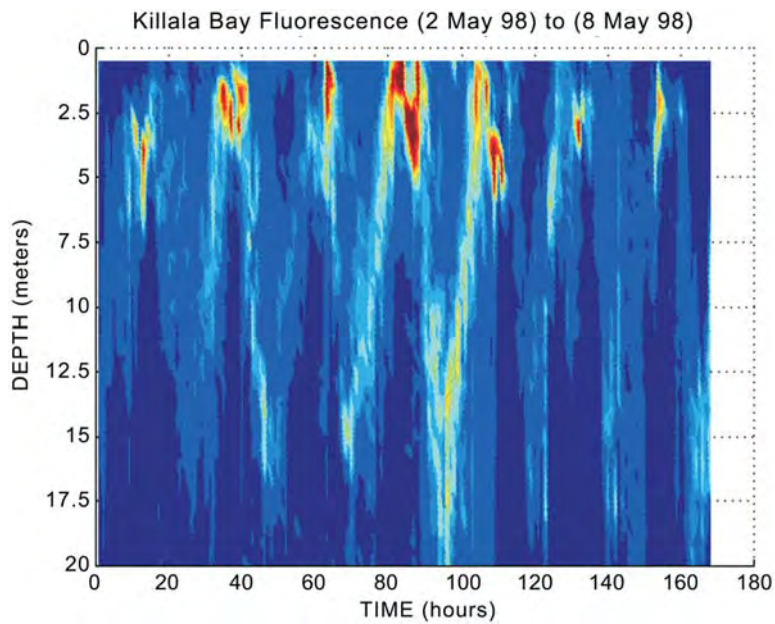


Figure 3.2.3. Time-depth fluorescence plot showing diel migration of the toxic dinoflagellate *Gymnodinium catenatum* at Killala Bay in the Huon Estuary, Tasmania. *In vivo* fluorescence of chlorophyll pigment is used to track the rhythmic movement of cells in the water column. From CSIRO Marine Research.

How will climate change and human activities alter coastal ecosystems, habitats, and living marine resources?

Coastal ecosystems are presently undergoing significant change. Anthropogenic activities, such as enhanced release of nutrients and other contaminants, alteration of freshwater discharge, and removal of selected species through fishing, are altering coastal dynamics, geochemical characteristics, and biological community composition. In addition to local influences, changes in global climate and other indirect effects may also alter coastal ecosystems in important ways. For example, sea-level rise, changing coastal wind regimes, and variations in oceanic thermohaline circulation may alter upwelling rates and source waters, thereby affecting coastal productivity. Increasingly frequent occurrences of low-oxygen “dead zones” in coastal waters have been linked to both increased nutrient input from coastal runoff and to changes in nutrient content of offshore source waters due to climate variability (see Sidebar 3.2).

Invasion of anthropogenic CO₂ into ocean waters is acidifying surface waters. Changes to date already exceed those associated with the glacial-interglacial transition and future increases are projected to be well in excess of the natural variability during at least the last 400,000 years. Increased acidification of surface waters by continued invasion of anthropogenic CO₂ is expected to impact ecosystems by hindering biogenic calcification and altering micronutrient abundance, chemical speciation, and bioavailability. Such changes would alter the species composition of coastal ecosystems and degrade the health and stability of coral reef systems.

Coastal ecosystems are structured by complex interactions among physical factors (e.g., light, temperature, mixing, turbulence, and currents), chemical factors (e.g., concentration, distribution, and bioavailability of macronutrients and micronutrients/trace elements that are required for life), and biological processes (e.g., primary production, grazing, predation, and respiration). When

viewed statically, individual factors may seem to exert considerable control or limit specific biological processes. However, the ocean is dynamic and it is the interactions among physical, chemical, and biological processes that determine the state of coastal ecosystems. Understanding the dynamic interplay among these factors requires a holistic, multi-parameter approach in which continuous measurements provide the basis for distinguishing interactions and feedbacks in this changing environment. Furthermore, linking basic environmental factors that are changing to the population dynamics of marine organisms requires detailed observations of the organisms themselves. Unfortunately, many details about basic characteristics such as cues for the timing of spawning and migration, are unknown. In many instances these may be linked to very specific environmental factors, although present knowledge is limited to that derived from net tows at fixed locations conducted at only a few times per year. Development of coastal observatories will make possible direct, continuous, simultaneous observations of organism behaviors and response to environmental forcing.

Role of Ocean Observatories

The ocean observatory infrastructure acquired through the OOI will provide a unique opportunity to measure the temporal and spatial scales of coastal ocean processes over a larger spectrum than previously achieved and will permit the development of new kinds of measurements of these processes. The collection of long time series will permit observations of infrequent, episodic processes that have not previously been observed from ships. Sustained observations also will permit a more rigorous and accurate assessment of long-term changes and temporal trends, a requirement of climate-change studies. Synoptic measurements over broad regions will permit the teleconnection of events and trends to be directly examined. These measurements may have immediate relevance in areas such as coastal ecosystem management (e.g., the direct observation of organism spawning and migration behaviors), but unexpected and unpredicted important observations are also anticipated.

SIDEBAR 3.2. HYPOXIA IN THE COASTAL OCEAN

Contributed by Jack Barth, Oregon State University, Scott Glenn, Rutgers University, and Oscar Schofield, Rutgers University

Hypoxic (low-oxygen) bottom waters on continental shelves are a growing problem for many countries. These conditions demonstrate the human capacity to degrade the ocean environment over hundreds of kilometers and, as demonstrated in the northern Gulf of Mexico, link events far inland to the ocean environment. Hypoxic conditions result from a variety of interacting processes, both natural and anthropogenic, so that detailed causes can differ from place to place and time to time.

Widespread hypoxic conditions are sometimes observed in the Mid-Atlantic Bight (MAB). In 1976, hypoxia affected nearly the entire New Jersey shelf, resulting in losses of over \$500 million to the shell-fishing and related industries. Recent observations suggest that interactions between seafloor topography and summer upwelling might underlie the low dissolved-oxygen concentrations, even though anthropogenic nutrient inputs had been previously implicated. The narrower West Coast shelves also experience hypoxia. In the summer of 2002, severe inner-shelf hypoxia off Oregon resulted in mass die-offs of fish and invertebrates. In the middle of the hypoxic region, mortality in commercial crab pots was over 75%. The low-oxygen bottom

water was traced to anomalous entrainment of cold, fresh, nutrient-rich subarctic waters into the region and the consequent production and sinking of coastal phytoplankton biomass.

Although hypoxia has been observed across a wide range of habitats, the specific processes that lead to this condition have not been characterized. Without process-level understanding, predicting hypoxia will not be possible. Determining the relative contributions of physical and biogeochemical processes requires the expanded measurement scales and advanced capabilities of ocean observatories. Continuous observations of water properties (temperature, salinity, velocity, and nutrient, phytoplankton, and oxygen content) are needed throughout the water column over spatial scales ranging from a few meters vertically to hundreds of kilometers across the coastal region. Real-time information from observatories, coupled with models, could direct responsive ship, mooring, and autonomous vehicle sampling programs to capture biological and chemical processes as events evolve. Thus, observatories have the potential to accomplish what previous expeditionary sampling could not: to significantly advance understanding of the component processes that control the formation of hypoxia.



Images from a remotely operated vehicle of a normal rockfish community off central Oregon in summer 2000 (left) and during the hypoxic event of July 2002 (right). Figure courtesy of D. Fox, Oregon Department of Fish and Wildlife.

Satellite remote sensing provides a tangible example of the potential benefits that can be achieved by applying even a modest set of sensors to broader, previously unobtainable scales of observations. Even with only a few sensor types, the synoptic views of surface properties provided by satellite remote sensing have revolutionized our view of mesoscale variability of the ocean. Through these observations, significant advances in all of the disciplinary sub-groups of oceanography have been made. It is anticipated that extending our scales of observations to include short-event time scales; sustained, long-term time scales; and regional to global, synoptic observations through the water column will similarly revolutionize our understanding of ocean processes.

In this context, numerous experiments can be envisioned. Many of the important transformations and transports in coastal ecosystems have been ascribed to episodic events. Yet, direct observations of these phenomena have generally not been achieved through expeditionary research efforts. To capture these events, a sustained presence must be achieved. Because process interactions are dynamic, sampling during events must be optimized to resolve, as fully as possible, the complex web of interactions that control ecosystem responses. The coastal ecosystem is also known to be undergoing change. Sustained observations are required to understand the causes of these temporal trends. However, ecosystem changes may be the result of variations in the frequency of short-term events or non-linear interactions between episodic and long-term trends. Therefore, measurements at high frequencies for extended time periods will be required to advance understanding of the changes.

Through a mix of initial efforts associated with IOOS and NSF-sponsored research programs, prototype observatories have been developed and installed in a variety of coastal environments. Valuable technical lessons have been learned through these activities. Additionally, these time-series measurements have already uniquely contributed to coastal research efforts and demonstrate the potential of this approach. However, these results also reveal that significant research and development is re-

quired to achieve the interdisciplinary diversity of measurements needed to advance understanding of coastal ecosystems and achieve the goals of operational observing systems. Supporting research and technology development is the principal goal of the OOI and its implementation is therefore an important aspect of the overall global observing effort.

3.3. Global and Plate-Scale Geodynamics

It has been nearly 40 years since plate tectonics revolutionized our understanding of how the movement and interaction of tectonic plates at Earth's surface are responsible for the formation of ocean basins, the uplift of mountains, the rifting of continents, and the global distribution of earthquakes and volcanoes. This scientific revolution has 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 geophysical observations, primarily seismic measurements, over the 70% of Earth's surface covered by oceans, 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 oceans. Although many of the instruments needed to make these measurements exist (e.g., hydrophones, seismometers, pressure sensors, and geodetic instrumentation), deployment of these sensors in the ocean basins 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. Inadequate spatial sampling is also a severe obstacle to understanding Earth's geomagnetic field. Adequate magnetic field models will require a global geomagnetic observatory spacing of no more than 2,000 km. Sampling durations of decades are desirable if phenomena such as core torsional oscillations, changes in core angular momentum, and accelerations of the magnetic field ("jerks") are to be understood.

The OOI infrastructure will provide the power, bandwidth, and two-way communication to instruments on the seafloor in regions far from land that are needed to fill critical gaps in existing land-based global geophysical coverage. The OOI will also provide the infrastructure necessary to install dense local networks of continuously recording sensors in geologically active areas on the seafloor to capture episodic events, such as earthquakes, submarine volcanic eruptions, rapid crustal deformation, or submarine landslides. Some of the long-standing and emerging new scientific questions this novel infrastructure will enable are briefly outlined below.

Examples of Key Scientific Questions

What is the pattern of convection in Earth's mantle and the origin and scales of mantle heterogeneity?

One of the most important and long-standing questions in geodynamics is the pattern of convection in Earth's mantle, and the origin and scales of mantle heterogeneity (Figure 3.3.1). For many years it was thought that the upper and lower mantle represented distinct geochemical reservoirs. However, over the past decade, advances in seismic tomographic imaging have shown that some subducting slabs extend well into the lower mantle, casting doubt on a simple layered convective model. In some cases, slabs appear to be confined to the upper mantle.

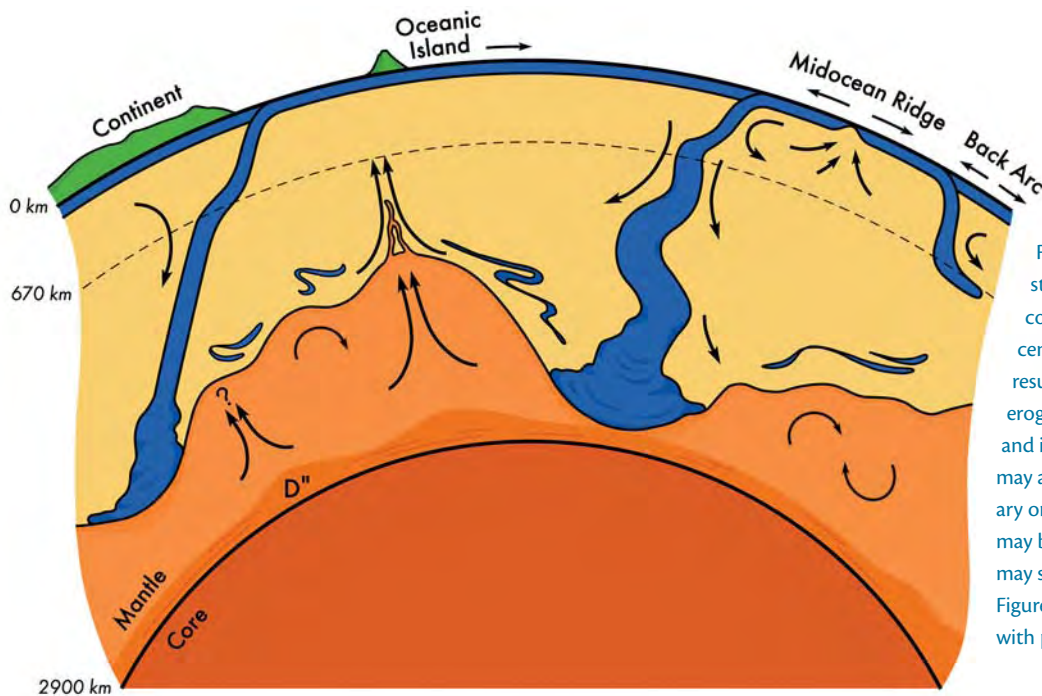


Figure 3.3.1. While Earth's internal structure has long been viewed as concentrically layered and static, recent seismological and geochemical results suggest that the mantle is heterogeneous on a variety of spatial scales and is highly dynamic. Mantle plumes may arise from the core-mantle boundary or the mid-mantle; subducting slabs may be confined to the upper mantle or may sink to the core-mantle boundary. Figure from Kellogg et al., 1999, reprinted with permission, AAAS.

In other cases, they appear to sink deep into the lower mantle although they often “fade away” in tomographic images well above the core-mantle boundary (CMB). It is unclear, however, whether slabs don't extend below this depth, or whether this is an artifact of poor seismic resolution in the lowermost mantle. Another very controversial issue in mantle dynamics is the origin of “hot-spot” volcanism—such as that which occurs in Iceland or Hawaii. In particular, there are widely varying views on whether hotspots rise as narrow hot jets from a thermal boundary layer, such as the core-mantle boundary, whether they form at various depths in the mantle, or whether this volcanism is caused by shallow lithosphere-scale processes. Because mantle plumes are relatively narrow, with diameters on order of a few 100 km at most, imaging plumes using conventional seismic tomographic techniques with data from only continental or island stations has been problematic.

Even a small number of seafloor seismic stations located in regions without islands (e.g., the South Pacific between Chile and New Zealand) would significantly improve

our ability to image plume conduits and subducting slabs in the mid- and lower mantle in the Pacific and address these important questions regarding mantle dynamics.

What are the properties of Earth's core, core-mantle boundary, and lowermost mantle?

The structure of Earth's CMB is one of the last frontiers in global seismology. The CMB plays a critical role in regulating heat flow from the core to the mantle, thereby influencing convection in the core and the dynamo that generates Earth's magnetic field. The CMB also plays an important role in mantle convection—it may be the source of at least some mantle plumes and may act as a reservoir for long-lived geochemical heterogeneities. Recent studies of the CMB have found evidence for extremely low seismic velocities, dubbed Ultra-Low Velocity Zones (ULVZ), but it is not clear what these features are. One clue about their origin comes from where they are found. The ULVZs appear to correlate with an area of widespread volcanism known as the South Pacific superplume and they don't seem to occur where subduc-

tion of the ocean lithosphere is occurring. However, coverage of CMB properties is very incomplete, especially in the southern hemisphere, largely because of a lack of stations in the oceans, and as a result, these ideas remain very speculative (Figure 3.3.2).

The Tonga Trench and other subduction zones in the western Pacific are the source of the most abundant large, deep earthquakes on Earth, and consequently are ideal sources for studies of the core-mantle boundary beneath the Pacific. However, the seismic waves from these events that sample the CMB beneath the Pacific can only be recorded at sites in the central equatorial Atlantic. A small number of seafloor seismic stations in the Atlantic Ocean would significantly improve our ability to resolve the structure of the Earth's outer core and core-mantle boundary.

What is the physics of earthquake nucleation and rupture propagation for different types of plate boundaries (subduction zones, transforms, spreading centers)?

Earthquakes at plate margins are the most important indicator of the state of stress and deformation in the lithosphere, and in some cases pose great risk to populations that live on or near these plate boundaries. Our knowledge of the nucleation and rupture processes of earthquakes along plate boundaries has been severely limited by the lack of stations in the immediate vicinity of ridge crests, subduction zones, and oceanic transforms, most of which lie beneath the oceans. Extending our study of earthquake processes to fault systems on the seafloor is essential for a more complete understanding of why earthquakes occur, what controls their size and frequency, and the hazards from related processes such as submarine landslides and tsunamis.

Megathrust events in subduction zones are responsible for some of the most devastating earthquakes and tsunamis on Earth (Figure 3.3.3). Long-term geophysical observations of these offshore fault systems are required to understand the physical processes preceding and accompanying megathrust earthquakes in order to devel-

op a better theoretical framework for predicting seismic hazards for a particular region. Seismometers and hydrophone arrays are also needed to detect and locate the small, but tectonically important, earthquakes currently missed by onshore networks, and to provide better constraints on the depths and focal mechanisms of larger events. Geodetic observations offshore (e.g., strain, tilt, vertical motion) can provide critical information on the nature and extent of deformation that has accumulated in the megathrust zone and, together with seismic data, can be used to assess the seismic potential and tsunami risk of different segments of a convergent margin. Other offshore observations that are needed for a better understanding of accretionary wedge and megathrust earthquakes are measurements of fluid flow and fluid pore pressures in offshore sediments, as fluid processes are

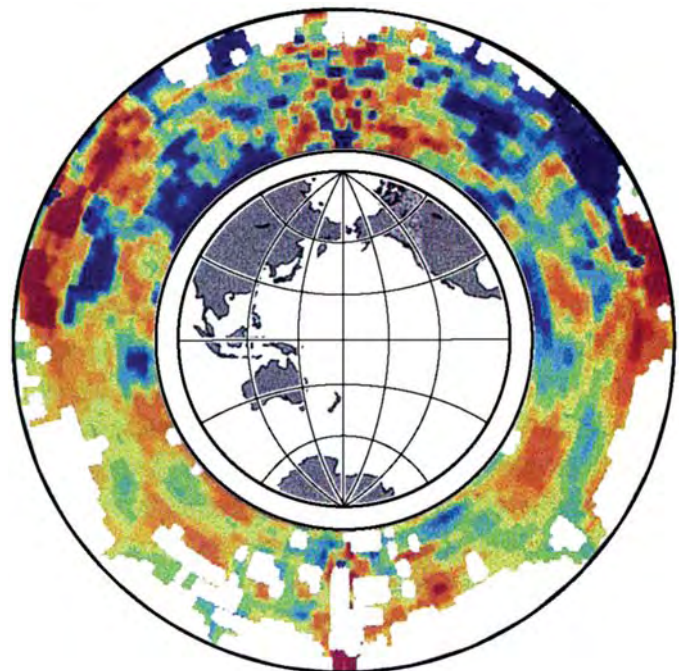


Figure 3.3.2. Polar cross-section of a 3-D seismic tomographic model (van der Hilst et al., 1997) of Earth's mantle. Blue colors indicate fast anomalies; red colors indicate slow anomalies. Note the poor resolution of this model in the southern hemisphere (white) because of the lack of seismic stations in the ocean. Figure from Boschi and Dziewonski (1999).

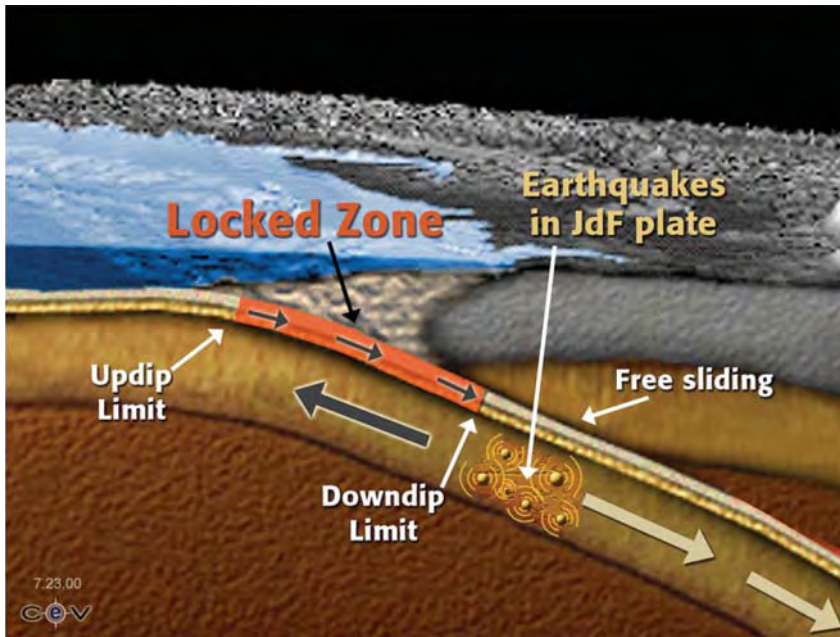


Figure 3.3.3. Schematic cross section of the Cascadia margin. Ruptures of the locked zone of a subduction zone megathrust are responsible for some of the most devastating earthquakes and tsunamis on Earth. Seismic and geodetic measurements made offshore, in combination with onshore measurements, can be used to determine the existence and dimensions of the locked zone and hence the seismic risk associated with the convergent margin. Image provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and the Center for Environmental Visualization.

likely to be an important factor controlling earthquake generation and will affect slope instability resulting from an earthquake.

Oceanic transform faults are also of interest to earthquake seismologists because they exhibit simpler and more predictable geologic, thermal, and tectonic conditions than continental strike slip faults, such as the San Andreas or Anatolian fault systems. On a global scale, oceanic transforms fail predominantly by aseismic slip—even the largest earthquakes on these faults rupture only a small portion of the total fault area. This behavior is essentially the opposite of continental faults where large earthquakes rupture entire fault segments and aseismic slip is a secondary process. Oceanic transforms thus offer an ideal natural laboratory for constraining the mechanical processes involved in faulting and lithospheric deformation. *In situ* seismic and geodetic recordings of large oceanic transform earthquakes at a seafloor observatory, combined with experimental rock mechanics data for the materials present at oceanic transforms, will be required to understand the physics of earthquake nucleation and rupture propagation at these faults.

Role of Ocean Observatories

Addressing the scientific questions outlined above will require seismic, acoustic, geodetic, and other geophysical measurements at seafloor observatories at all three major scales of the OOI (global, regional, and coastal). This multi-scale approach has been used with great success on the continents to study Earth structure and tectonics, and is strongly advocated for the oceans.

At the global scale, the seismic observations enabled by the OOI will help complete the global coverage of geophysical observations and provide much-improved images of deep Earth structure. Large gaps (>1000 km from the nearest land seismic station) exist in the global network of broadband seismic stations in the oceans that cannot be filled with island stations, particularly in the eastern Pacific and Southern Oceans (Figure 3.3.4). Without broadband seismic stations in the oceans, the resolution of mantle tomographic models will always be seriously compromised.

Over the past decade significant progress has been made in addressing the technical problems associated with the deployment and recording of observatory-quality seismic stations on the seafloor. The 1998 Ocean Seismic Network Pilot Experiment, for example, demonstrated the technical feasibility of deploying seafloor and buried broadband seismometers and installing a borehole broadband instrument in a shallow drillhole using wireline re-entry technology. The borehole data collected in this pilot experiment were comparable or superior to seismic data from a nearby island station. The International Ocean Network (ION) program has established the long-term goal of occupying 20-25 sites in the oceans with perma-

nent, borehole broadband seismometers in order to complete the Global Seismic Network (Figure 3.3.4). In the short term, even occupying a small number (6-10) of sites in the Southern Ocean and equatorial Atlantic would significantly improve the imaging of deep Earth structure.

A regional-scale cabled observatory in the Northeast Pacific would provide a unique opportunity to investigate the inter-related processes that control the formation, evolution, and destruction of the Juan de Fuca plate and its interactions with the North American continental margin. This region incorporates a remarkable array of tectonic features in a relatively small area, including all of

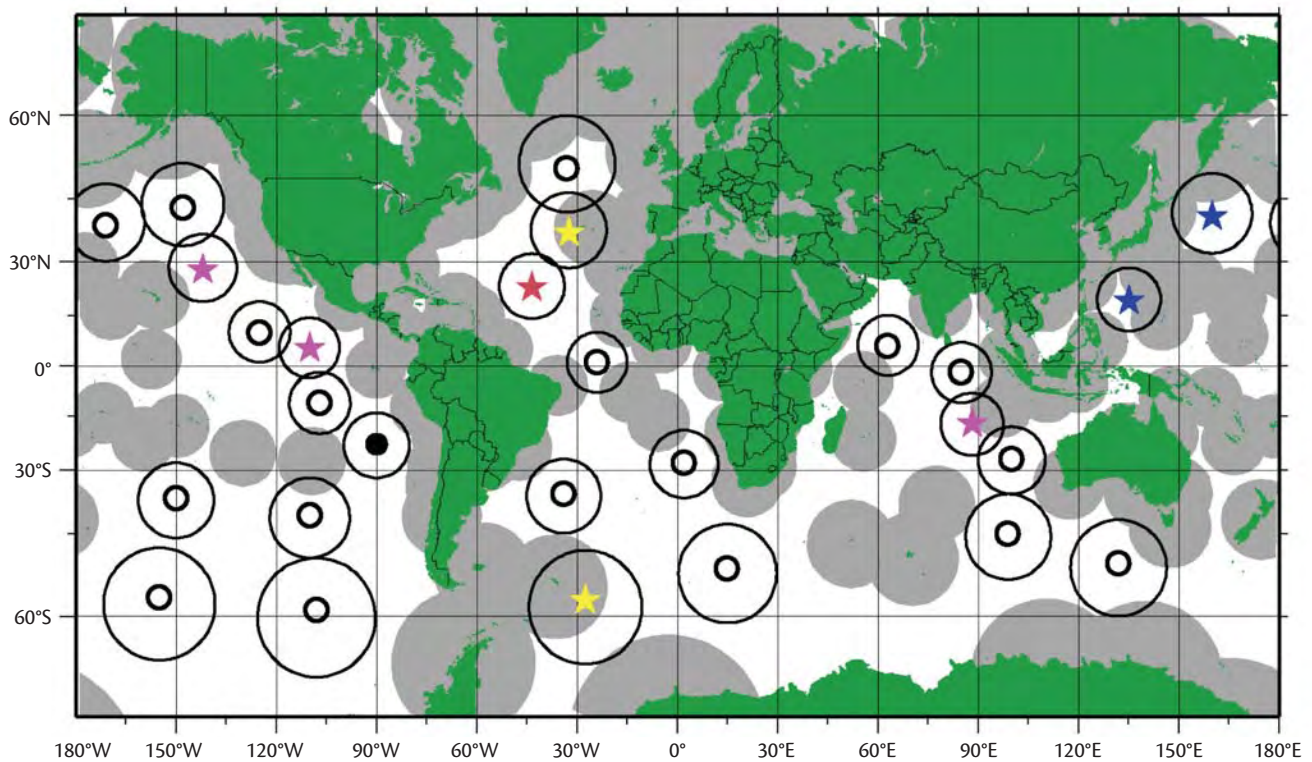


Figure 3.3.4. Those areas in the world's oceans that lie more 1000 km from the nearest land or island seismic station are shown in white. Large gaps exist in the global network of broadband seismic stations in the oceans that cannot be filled with island stations, particularly in the eastern Pacific and Southern Oceans. Without broadband seismic stations in the oceans, the resolution of mantle tomographic models will always be seriously compromised. The sites proposed by the International Ocean Network (ION) program for obtaining improved global seismic and geophysical coverage in the oceans are shown by symbols surrounded by black circles with a radius of ~ 1000 km. The different symbols show different levels of progress in establishing these sites: the blue stars are presently operating borehole observatories, the maroon stars are sites at which holes have been drilled by ODP but have not yet been instrumented, and the solid and open black circles are high priority ION and OSN sites proposed, but not yet drilled. Figure courtesy of Ralph Stephen, Woods Hole Oceanographic Institution.

the major types of plate boundaries. Understanding the lithosphere-asthenosphere system at the plate scale will require coincident seismic, geodetic, and other geophysical measurements on the seafloor at multiple scales over a period of a decade or longer.

At the 2003 Regional Cabled Observatory Network of Networks (RECONN) Workshop (Purdy and Karl, 2004), the basic elements of a plate-scale geodynamics observatory were developed (Figure 3.3.5). The plate-scale observatory includes a regional array of seismic, acoustic, geodetic, and electromagnetic instruments at approximately 30 sites with a nominal spacing of about

100 km across the entire Juan de Fuca, Explorer, and Gorda plates. Some sites are located on the adjacent Pacific plate to ensure good resolution of the Pacific-Juan de Fuca plate boundary, and the accurate determination of Pacific, Juan de Fuca, and North America relative plate motions. To study the interactions among seismic activity, crustal deformation, and hydrogeologic processes along plate boundaries, dense arrays of sensors with an aperture of a few kilometers will be required at a small number of carefully selected sites along each of the three major active plate boundaries—the Juan de Fuca Ridge, the Blanco fracture zone, and the Cascadia margin subduction zone (see Sidebar 3.3).

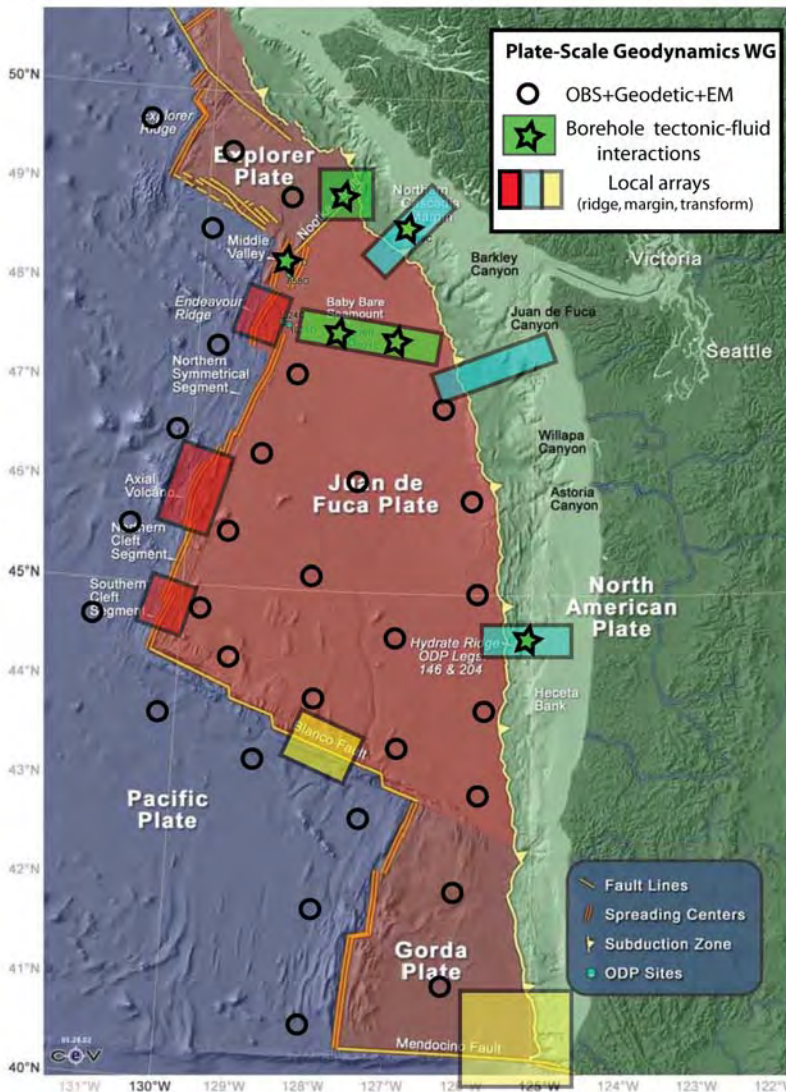


Figure 3.3.5. The basic elements of a plate-scale geodynamics observatory in the Northeast Pacific as developed at the 2003 RECONN Workshop (Purdy and Karl, 2004). The black open circles are nodes equipped with broadband seismometers, a hydrophone or vertical hydrophone array, transponders for acoustic/ GPS plate motion measurements, and seafloor magnetometers and electric field instruments. Colored boxes show locations of dense arrays of sensors designed for plate boundary studies at the Juan de Fuca Ridge (red), Cascadia subduction zone (turquoise) and Blanco/Mendocino transforms (yellow). Stars show existing ODP or planned IODP boreholes.

SIDEBAR 3.3. A CASCADIA MARGIN EARTHQUAKE AND TSUNAMI OBSERVATORY

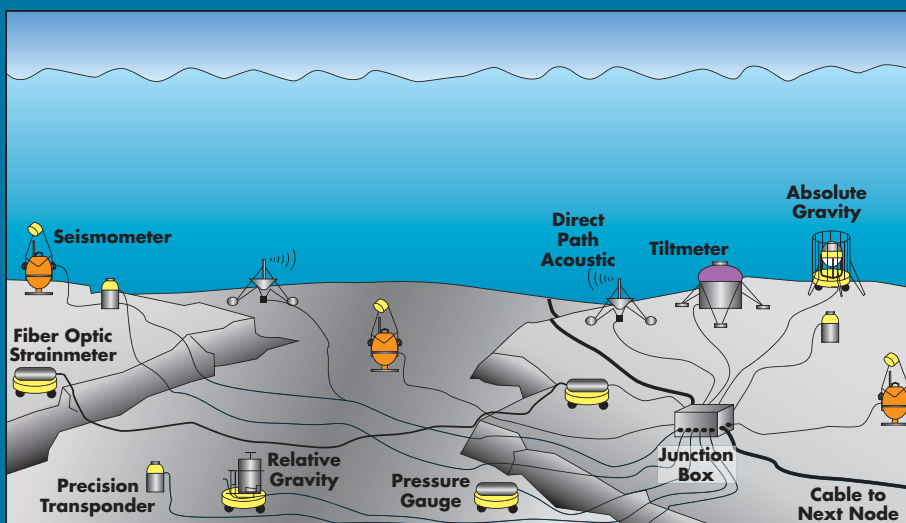
Contributed by Robert Detrick, Woods Hole Oceanographic Institution

The great Sumatra earthquake on December 26th, 2004, and the devastating tsunami that followed this event, have highlighted the urgent need to improve understanding of potential earthquake and tsunami hazards in regions where oceanic lithosphere is being subducted. Megathrust earthquakes occur when a locked zone that develops between the subducting and overriding plates suddenly ruptures (Figure 3.3.3). These events are responsible for some of the most devastating earthquakes and tsunamis on Earth.

The Cascadia subduction zone, which extends from northern California to southern British Columbia, has a high seismic risk from these kinds of events (the last major megathrust event along this margin occurred January 26, 1700, rupturing a fault along ~1000 km of the margin and causing a major tsunami that struck Japan). Determining the seismic potential of megathrust events along this margin has been hampered by lack of observations offshore. Offshore seismic and geodetic observations can provide constraints on the updip limit of the locked zone (which is a primary control on tsunami generation) and on the length of the rupture zone downdip (which controls the magnitude of megathrust events and hence the seismic risk to inland cities) that cannot be obtained from land stations alone. Long-term earthquake monitoring offshore will also constrain the distribution and extent of faulting in the incoming plate

that may be reactivated beneath the margin. Recording wave propagation up and down the dipping slab will constrain its velocity structure and thus its thermal structure and petrology, important factors controlling earthquake generation.

A Cascadia Margin Earthquake and Tsunami Observatory has been proposed as part of the OOI's planned Northeast Pacific regional cabled observatory. Two main subduction and accretionary wedge observatory sites are planned, corresponding to existing ODP and planned IODP boreholes off southern Vancouver Island and off Oregon (Hydrate Ridge). An additional site off Washington State could address the differences in accretionary wedge structure (landward- and seaward-verging thrusts) along the Cascadia margin. Another high-priority site is over the Nootka transform fault off Vancouver Island. Each subduction zone earthquake observatory will be a transect ~50 to 75 km long crossing the shelf-slope. In each transect, 10 broadband seismometers and strong-motion accelerometers will be installed. Geodetic sensors will be installed to measure tilt and vertical uplift associated with strain accumulation in the overlying plate. Additional sensors needed for these observatories include magnetic and electric field instruments, borehole temperature and pressure sensors, and instruments for fluid monitoring and sampling. All data will be telemetered to shore in real time for analysis and interpretation.



Cartoon showing a seafloor geophysical observatory containing seismometers and a variety of geodetic instrumentation to measure crustal deformation and seismicity associated with an offshore subduction zone fault. The seafloor junction box provides power to these instruments. Data are telemetered to shore in real time or near-real time via a fiber optic cable.

3.4. Turbulent Mixing and Biophysical Interactions

Turbulent mixing 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 ocean's 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 huge range of scales, from molecular to 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) also are themselves non-linear and complex. As a result, long time series are needed to characterize statistical measures of these processes. However, obtaining continuous, simultaneous information on mixing and responses at the required spatial resolution (millimeters to tens or hundreds of kilometers) 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. High power and communications bandwidth are needed to make sustained measurements with multi-frequency acoustic and chemical sensors, multi-wavelength optical sensors, and holographic and video/still pho-

tography. Interactive instrument control and adaptive sampling capabilities are needed to “capture” short-lived episodic turbulent events. Thus, significant advances in the investigation of ocean mixing and biophysical interactions will require an observatory approach.

Examples of Key Scientific Questions

What role does vertical mixing in the ocean's interior play in determining the global distribution of heat and nutrients in the ocean?

An accurate representation of diapycnal (across density surfaces) eddy fluxes is needed, in combination with information on larger-scale flow fields, to model basin-scale processes such as the ocean's thermohaline circulation and smaller-scale processes such as the supply of nutrients from the deep ocean to the euphotic zone. For example, general ocean circulation models show that the rate of global ocean overturning, hence the poleward heat transport that affects global climate, is very sensitive to the value assumed for diapycnal diffusivity. There are still very few direct measurements of this quantity and there remains a strong need for *in situ* observations in a variety of different oceanic regimes. The scarcity of data arises because *in situ* turbulent flux measurements are technically very difficult to make. Because mixing is dominated by a few rare, energetic events, and because these events are highly variable in both space and time, it is difficult to characterize transport processes in any one region without sustained observations.

In the past few years there has been significant progress in attacking the important problem of quantifying ocean diapycnal mixing. Measurements of diapycnal eddy diffusion are now possible with *in situ* tracer experiments and microstructure studies. These field experiments and satellite altimetry data have been used to demonstrate that the dissipation of semi-diurnal tidal energy over rough seafloor topography, both along shallow continen-

tal margins and in the deep ocean, can significantly enhance vertical mixing. Indeed, as much as one half of the mixing energy required to maintain the ocean's meridional overturning circulation could be supplied by the tides (Figure 3.4.1). However, our knowledge of the spatial and temporal pattern of diapycnal mixing in the oceans on a global scale is still grossly incomplete.

To understand ocean mixing processes better, *in situ* measurements are needed in different turbulence regimes (e.g., smooth and rough bottoms, shallow and deep water) over long periods to characterize rare events. New techniques are also needed to more directly measure turbulent fluxes of momentum and water properties such as heat, salt, and nutrients. The long-term goal will be to develop parameterizations of vertical mixing that account, in an integrated sense, for turbulent mixing of momen-

tum, water properties, nutrients, and biota within the water column. Different quantities may not mix at the same rate so the approach to the problem needs to be as interdisciplinary as technology will allow. Understanding these complex phenomena is a crucial first step in developing quantitatively valid models of regional and global climate and biogeochemical processes.

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?

The oceanic mixed layer, where turbulent mixing overcomes the stable, upper-layer density stratification, is the contact zone between the ocean's interior and the atmosphere. The main energy source for this upper-ocean

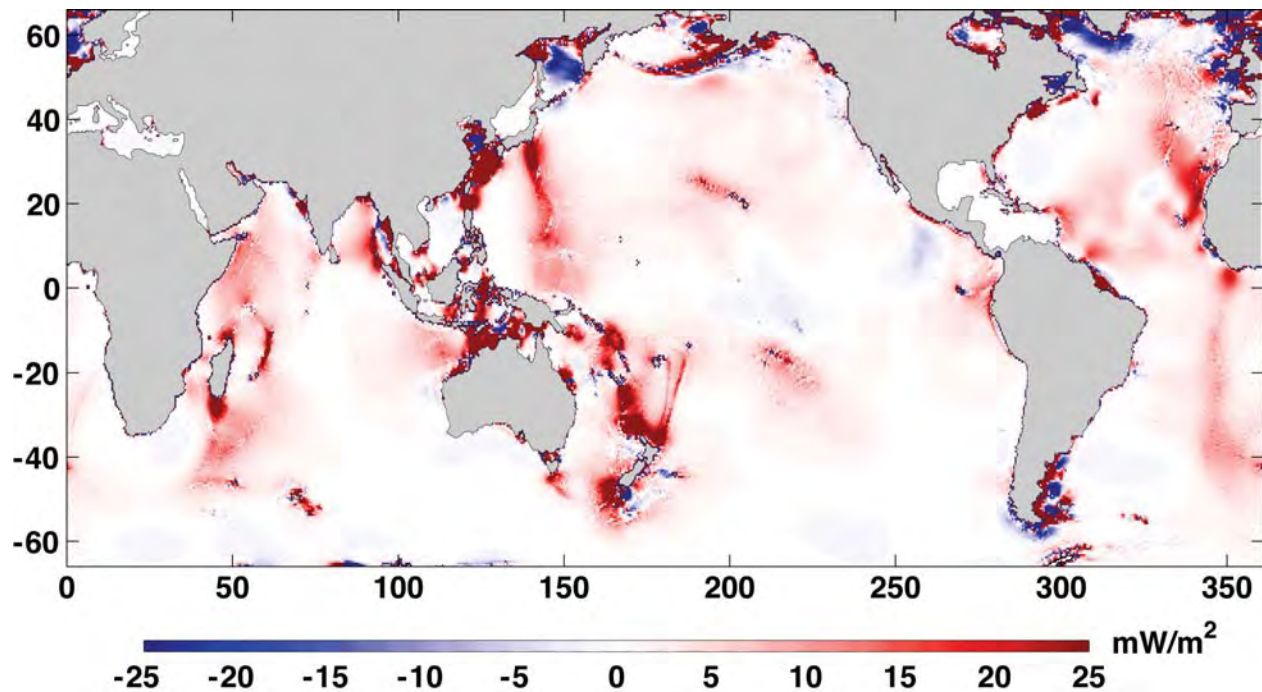


Figure 3.4.1. The distribution and magnitude of energy dissipation of the lunar semi-diurnal tide derived by least-squares fitting of equations expressing the conservation of mass and momentum with satellite-measured sea level data. Approximately 25-30% of the total dissipation of lunar semi-diurnal tidal energy occurs in the deep ocean, generally over areas of rough topography, rather than over shallow continental shelves. As much as half of the mixing energy required to maintain the large-scale thermohaline circulation of the ocean could be supplied by the tides. Figure after Egbert and Ray (2001).

mixing is atmospheric forcing by wind stress and buoyancy loss through evaporation and cooling. The transfer of greenhouse gases, like CO₂, between the ocean and atmosphere is believed to be mainly controlled by the breaking of capillary ripples and waves, while subsurface CO₂ concentrations will be strongly determined by biological activity, water column chemistry, and turbulent exchange with deeper waters.

Because of the importance of mixed-layer formation, and its seasonal variation, to the transfer of sensible and latent heat between the ocean and atmosphere, this process has been widely studied and several models of mixed-layer formation have been developed. However, there are still many outstanding problems regarding mixed-layer formation, including: (1) the processes responsible for wind mixing at the base of the mixed layer (e.g., breaking waves, Langmuir circulation); (2) the relative importance of storms in seasonal transfer of heat from the mixed layer to the atmosphere; and (3) the relative importance of wind-driven turbulence, large eddies, or shear in the entrainment of stratified water into the mixed layer. All of these science drivers require measurements that extend over several seasonal and interannual cycles and that not only describe the larger-scale changes associated with air-sea interaction, but resolve the smaller-scale processes that drive these changes. A critical area of study is the remote Southern Ocean where shipboard observations are restricted to just a few months of the year.

What role does vertical and horizontal mixing play in determining plankton community structure in the upper ocean?

Planktonic organisms often live in a surface layer strongly influenced by turbulence at virtually all scales. The structure of these communities may be directly affected by turbulent modulations in nutrient and light availability, and by biomechanical stresses. Indirect effects might include turbulence-induced behavioral changes on grazing, vertical migration, predation, or reproduction (egg fertilization or larval dispersal). Different species are adapted

differently to these effects (e.g., diatoms are considered to be characteristic of energetically mixed regions, while flagellates are more typically found in stratified environments), so species composition in a particular area can depend critically on turbulence.

Our understanding of exactly how turbulence affects ecosystem structure remains primitive. For example, we need to understand how individual organisms behave and interact with other organisms on scales relevant to their environment. At the level of a single organism, turbulence influences the rate of supply of oxygen and nutrients to individuals as well as the removal of waste products (Figure 3.4.2). It also affects the ability of an organism to sense and track chemical and mechanical cues in searching for food and mates or avoiding predators. Intermediate levels of turbulence enhance encounter rates between predators and prey, while high turbulence reduces the effective hydro-mechanical detection distance. Recent studies suggest that zooplankton respond to the magnitude of variance in the environment and not to mean conditions. This dependence on variability implies that non-linear biophysical couplings, which affect ecosystem structure, need to be studied continuously over the time scale of many ecological shifts.

Thus, observatory-based time series that simultaneously and continuously measure the vertical distribution of biota (phytoplankton, zooplankton, fish), turbulence and physical properties (velocity, temperature, salinity, density) in a range of settings are needed to characterize these biophysical interactions over spatial and temporal scales relevant to individual organisms and populations. Biosensors that require high-frequency sampling to characterize small-scale interactions (e.g., high-resolution imaging systems and multiple sample collection and analysis systems) will benefit from the power and bandwidth offered by cabled observatories (see Sidebar 3.4). Biological hot spots and thin layers require adaptive sampling to characterize these features and their spatial and temporal formation and dissipation.

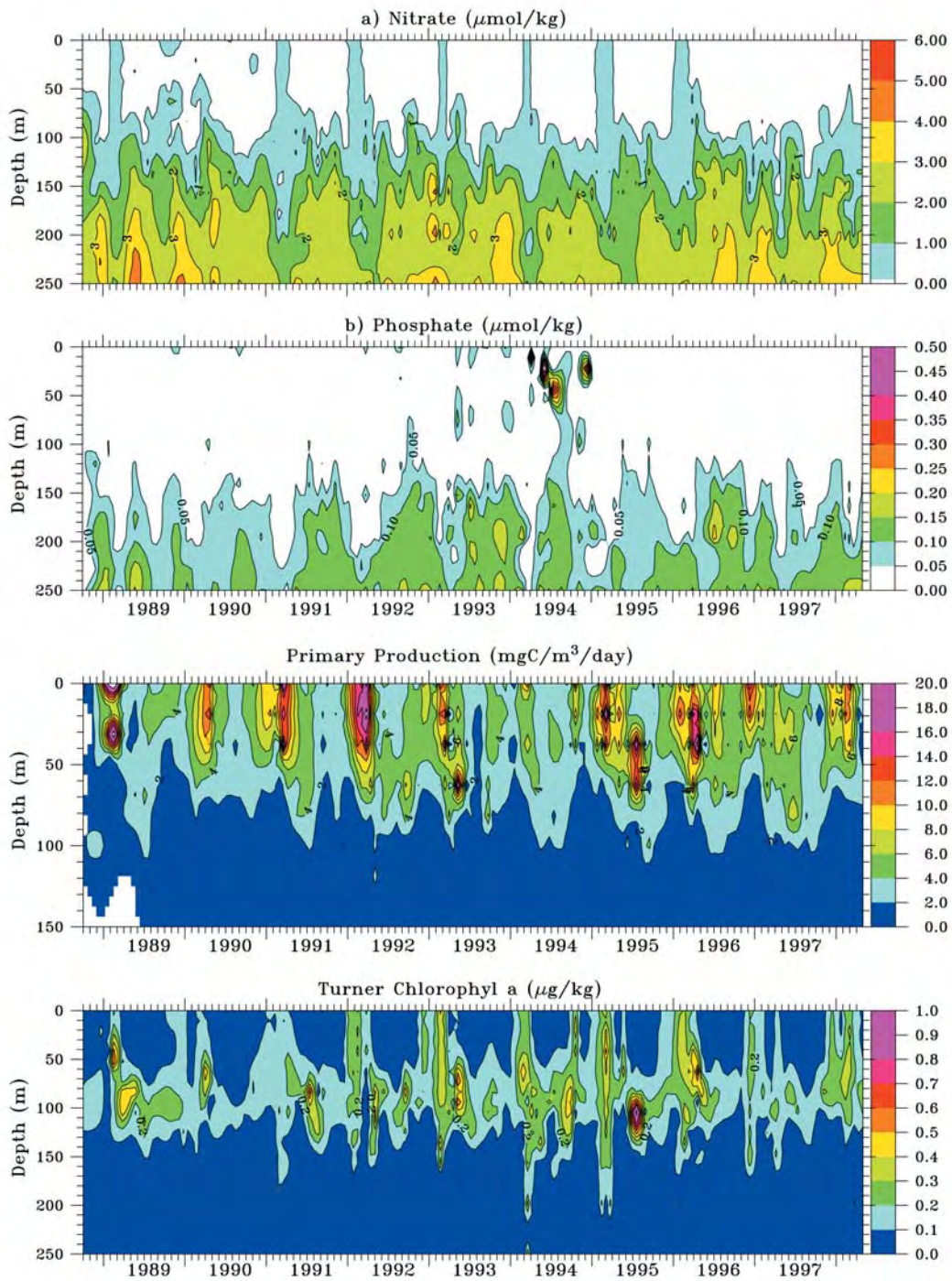


Figure 3.4.2. An example of annual variations over the past decade at the U.S. JGOFS Bermuda Atlantic Time Series Study (BATS) station. (a) nitrate concentrations, (b) phosphate concentrations, (c) primary production, (d) chlorophyll. Nutrients are mixed upwards into surface waters through eddy diffusion throughout the year; convective overturn deepens the mixed layer during fall/winter leading to further mixing. Figure modified from Steinberg et al. (2001).

SIDEBAR 3.4. PHYTOPLANKTON DYNAMICS ON THE NEW ENGLAND INNER SHELF: TIME-SERIES OBSERVATIONS AT THE MARTHA'S VINEYARD COASTAL OBSERVATORY

Contributed by H. Sosik, Woods Hole Oceanographic Institution

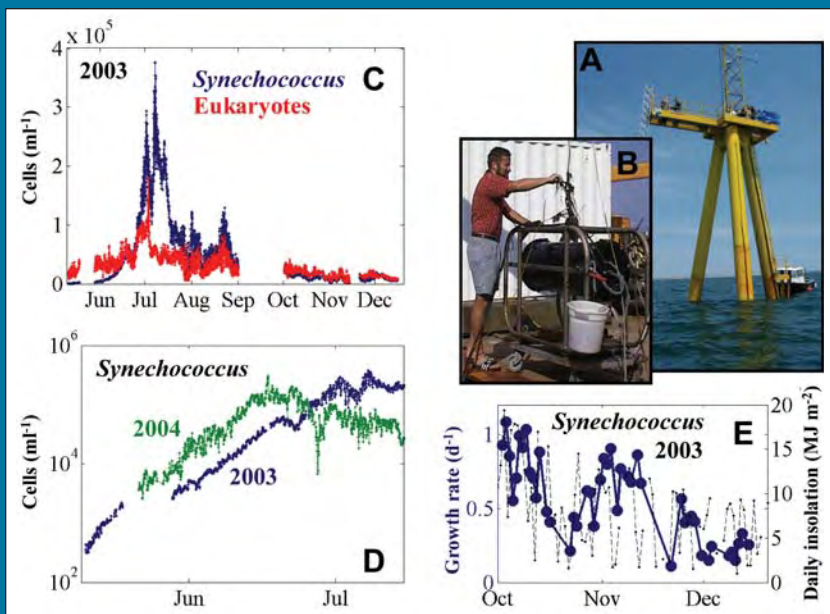
Cabled coastal ocean observatories combined with new sensor developments are permitting studies of plankton community structure and rate processes with unprecedented detail. One such example is at the Martha's Vineyard Coastal Observatory (MVCO), a cabled research facility on the inner continental shelf of the northeastern United States. The MVCO is near dense human populations and is sensitive to natural and human-induced perturbations on scales ranging from episodic to climatic. The MVCO includes a meteorological mast, an undersea node at a depth of 12 m, and an offshore tower (panel A) that is at a water depth of 15 m, spans the water column, and extends approximately 20 m into the atmosphere (see <http://www.whoi.edu/mvco>). The node provides continuous power and two-way communications for a variety of air-side and underwater instruments. On-going time-series observations at MVCO are a beginning to provide the integrated and sustained observations needed to better characterize and understand ecosystem effects on primary producers and throughout the marine food web.

Since 2003, FlowCytobot (panel B), a custom-built submersible automated flow cytometer (Olson et al., 2003), has been deployed at the offshore tower during spring to autumn. Flow-

Cytobot makes near-continuous measurements of pico/nano-phytoplankton abundance, cell size, and cell fluorescence characteristics. The cell abundance data are affected by spatial patchiness combined with water mass advection. Nonetheless, the observations show a classic late spring bloom of the cyanobacterium *Synechococcus* that is accompanied by a more modest increase in abundance of picoeukaryotic phytoplankton (panel C). Springtime blooms, usually initiated by seasonal increases in water temperature and light availability, are modulated by changes in nutrient availability and grazing pressure. Because of the spatial and temporal scales associated with traditional monitoring approaches, long-standing fundamental questions about how these factors interact to regulate seasonal patterns and about why blooms vary in timing and extent from one year to the next (panel D) remain largely unanswered.

Observatory-based sensors like FlowCytobot can provide extended high-resolution time series linked directly with physical and chemical sampling, leading to new insights. FlowCytobot observations provide cell abundance data and also diel patterns in cell-size distributions that permit time series of daily growth rates to be determined (Sosik et al., 2003). These growth

rates reflect a population's physiological response to changes in physical forcing such as light and nutrient availability. For example, during autumn at MVCO, there is a general decline in *Synechococcus* growth rates due to seasonal trends in incident radiation and temperature (which decreases from 18° C in October to <5° C); superimposed on this trend are periods of severely depressed growth due to cloudy weather (panel E).



How is benthic community structure affected by near-bottom turbulent events?

The structure and variability of the turbulent bottom boundary layer (BBL) is, together with seafloor substrate type, a major factor influencing the structure of benthic biological communities. However, our knowledge of the processes occurring in the BBL is still very limited. For example, tides and waves are expected to make the BBL much more energetic on shallow continental shelves than in the deep sea, but the impact of these differences on benthic community structure is still largely unknown. Episodic, turbulent “mega-events” are widely believed to have a major effect on both coastal and deep-sea benthos. These events can include density-driven turbidity flows that extend for many tens of kilometers across the continental shelf or down the continental slope. In shallow coastal regions, infrequent but intense interactions between surface (wind-driven) and bottom (current- and wave-driven) boundary layers can occur during major storms such as hurricanes. Instability and subsequent movement of sediment on continental slopes, due to earthquakes, and gas or groundwater discharge, is potentially a major means of sediment transport to the deeper ocean along continental margins.

The effect of these events on benthic community structure, and how benthic communities respond and recover from these episodes, is still very poorly understood. Benthic turbulent events are, by their nature, episodic and unpredictable for more than a few days in advance, so that sampling these crucial processes requires an enduring presence that is independent of the ability of ships to operate in extreme conditions. Thus, the installation of continuously recording, long-term ocean observatory sensor networks with two-way communication and adaptive sampling capabilities will be essential for future studies of BBL processes. These networks should include physical measurements (e.g., turbulence, currents) as well as water column geological, geochemical, and biological sensors and optical systems to assess the evolving state of benthic communities.

Role of Ocean Observatories

There are several ways that ocean observatories can advance the study of near-surface, water-column, and benthic turbulence in the oceans and its effect on biological processes. The observatory infrastructure will provide the means to measure turbulence and ecosystem properties continuously over long periods at a single location. Turbulent flow, and the response of ecosystems to turbulence-induced changes in their physical environment, are inherently unstable, non-linear, and exceedingly complex. These processes are modulated by diurnal, seasonal, and interannual cycles, as well as by unpredictable, episodic events (e.g., major storms or turbidity flows). Sufficiently long time series (at least several years) will be required to characterize this variability, even in a statistical sense, and separate it from variations in mean conditions. Even longer time series (several decades) will probably be necessary to observe variations in ocean mixing and ecosystem community structure that are associated with interannual, regional, or global changes in ocean circulation or climate (e.g., ENSO decadal variations).

Ocean observatories will also provide access to the upper ocean, either through buoys or through risers or “trees” extending upward from seafloor nodes into the mixed layer (Figure 3.4.3). They will supply the power and communications bandwidth required for extended acoustical, chemical, and biological measurements. Furthermore, because surface buoys will extend above the water’s surface, ocean conditions and air-sea fluxes can be reliably linked to atmospheric measurements. Observatories will provide the two-way communication and interactive instrument control necessary to respond to episodic turbulent flow events and document their biophysical response. The power and data requirements of the physical, chemical, and biological sensors required to make these measurements, and the profilers needed to sample the full water column, would not be feasible with a conventional, autonomous mooring or with mobile platforms such as profiling floats or gliders.

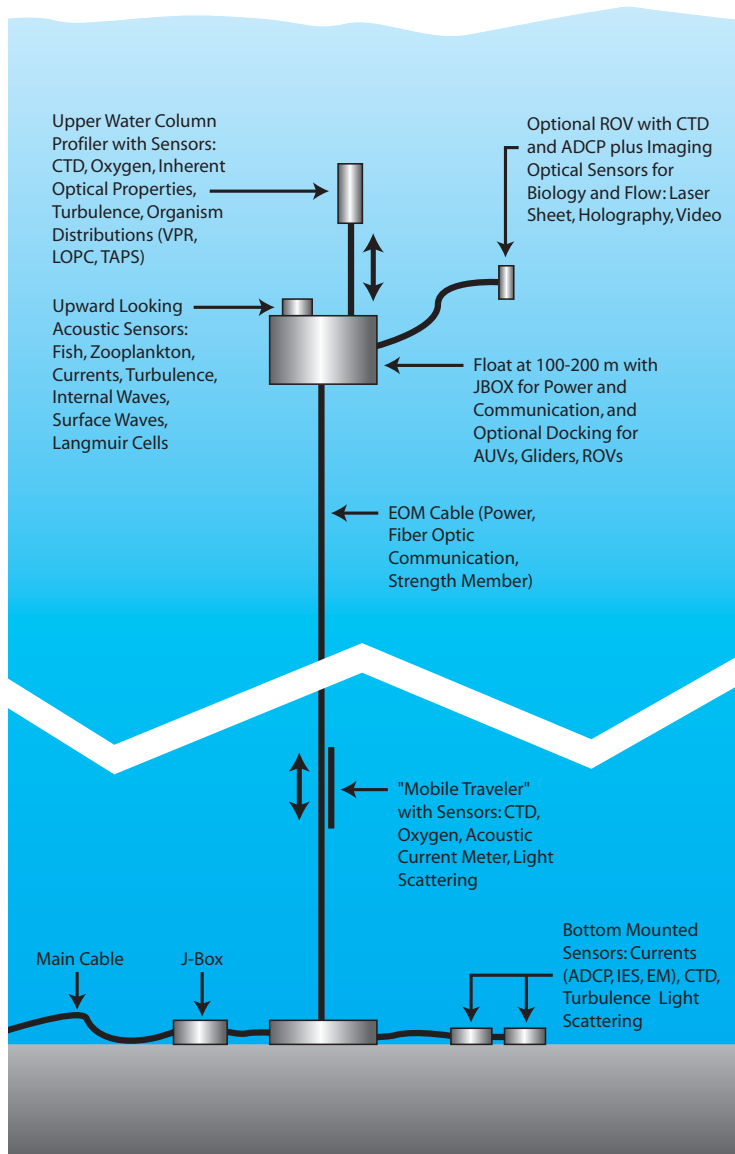


Figure 3.4.3. Notional design of a cable-linked subsurface mooring for investigating turbulent flow and biophysical interactions in the deep ocean. An electro-optical-mechanical (EOM) cable links a sub-surface measurement platform node with a seafloor junction box and provides power and two-way, high-bandwidth communication to sensors on the platform. These “EOM trees” will support three types of sensor packages: (1) sensors mounted on a platform atop a vertical riser at about 200 m depth, (2) a profiler that can collect data from 200 m depth to the sea surface, and (3) a crawler that can make repeated profiles between the seafloor and the platform node. Sensors at this observatory will simultaneously measure the vertical distribution of biota (phytoplankton, zooplankton and fish), current velocity, turbulence, and physical properties (temperature, salinity, density). The node will provide docks for AUVs, allowing repeat surveys of water column properties around the observatory site.

Ocean observatories will also provide the power, data communication, and docking infrastructure to support mobile vehicles like AUVs or satellite nodes (linked acoustically or by cable back to the central node) that can be used to expand the “footprint” of observations from a single point to a volume of ocean around that point. This is crucial for studies of biophysical interactions. Although observations at a single site will provide temporally (and vertically) well-resolved measurements, they can be aliased by horizontal variability in the underlying

fields. Satellite nodes or AUVs, equipped with appropriate physical, chemical, and biological sensors, will provide a three-dimensional characterization of these processes sufficient to separate advective (spatial) changes from true temporal variations. Taken together, ocean observatories will provide quantitative new measurements of upper ocean conditions and fluxes that will improve our understanding of biogeochemical cycles, ecosystem community structure and the ocean’s role in weather and longer-term climate variability.

3.5. Fluid-Rock Interactions and the Sub-Seaflor Biosphere

The upper oceanic crust comprises the largest aquifer on Earth (Figure 3.5.1). 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. On ridge flanks and along continental margins, these fluids react with oceanic 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 enrich the fluids in volcanic volatiles, dissolved chemical species, or carbon mobilized by post-depositional processes in sediments.

The nutrients in these fluids sustain a vast, microbial biosphere below the seafloor that is just beginning to be explored (Figure 3.5.2).

The overall geological, chemical, and biological significance of these processes 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.



Figure 3.5.1. Venting from ridge crests, subduction zones, and transform faults. All plate boundaries and many plate interiors vent microbe-bearing fluids into the deep ocean continuously and episodically. A. Unpredicted episodes such as magmatic eruptions at mid-ocean ridges increase nutrient (CO_2) output and venting volume by as much as a factor of 100, resulting in extensive microbial blooms. Organisms and flocculated by-products of microbial activity are released into the water column for weeks to months following eruptive events. B. Sediment-rich passive and active margins are important biotopes. Many of these sites host CH_4 gas hydrate that is in part biogenic in origin. The role of microbial communities is of intense interest because CH_4 in hydrates may represent more than double the total amount of carbon in known fuel reserves, it is a clean-burning potential fuel, but it is also a potent greenhouse gas under the right circumstances. C. Along transform faults boundaries, carbonate vent systems host methane-metabolizing microbial communities linked to exothermic reactions between mantle rocks and seawater. These reactions generate high pH and H_2 - and CH_4 -rich fluids. Such systems may last for thousands of years. Figure courtesy of Deborah Kelley, University of Washington.

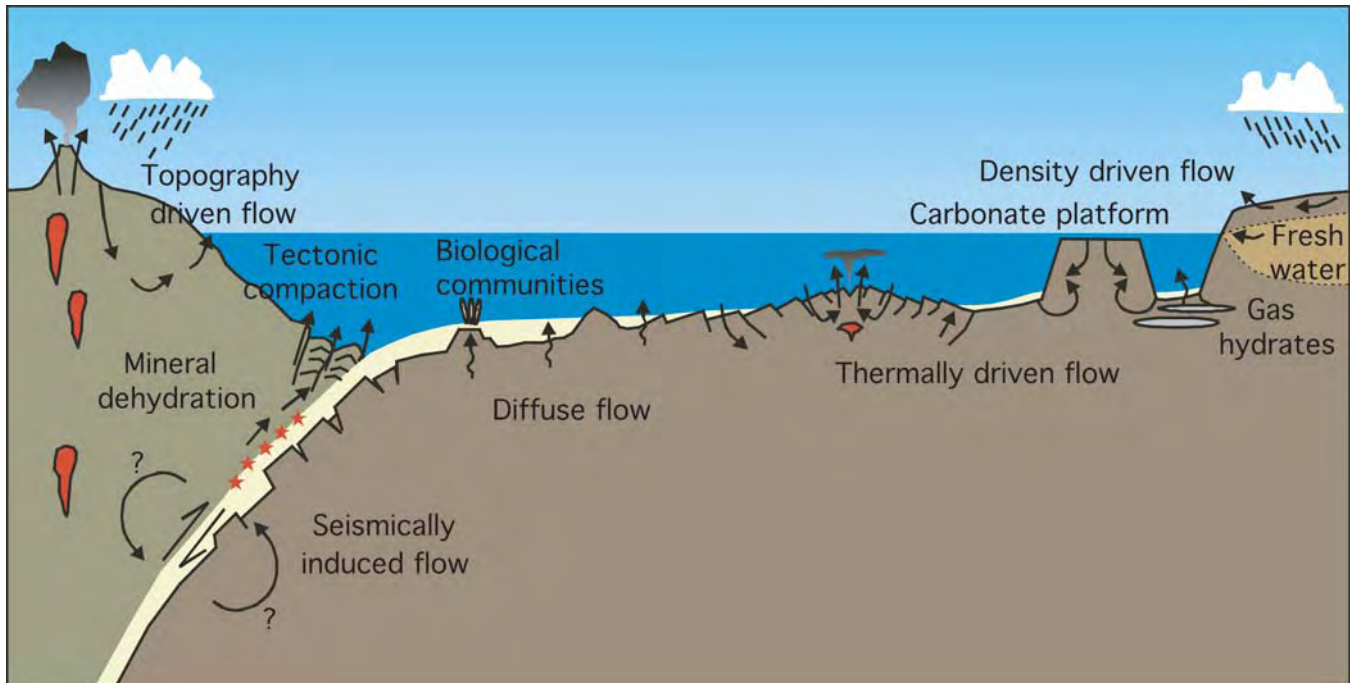


Figure 3.5.2. Sub-seafloor fluid flow systems in geological, biological, and hydrographic environments. Many seafloor and all sub-seafloor ecosystems are inextricably linked to, and perhaps an inevitable consequence of, the flow of energy and material between the earth's crust and the deepest portions of the overlying ocean. The direct linkages between life and planetary processes operating along deep-sea spreading centers, subduction zones, and transform faults, as well as mid-plate circulation, can only be understood through tightly integrated studies across a broad range of disciplines in geophysics, geology, chemistry, biology, and oceanography. Figure from JOIDES Hydrogeology PPG Report (2001), <http://poseidon.palaeoz.geomar.de/panels/reports.html>.

There is increasing evidence that transient events—earthquakes, volcanic eruptions, massive slope failures—play a critical role in many different environments, including mid-ocean ridges, passive and active margins, and in the fore-arc and back-arc regions of subduction zones. These transient events, which may last only hours or days, are very difficult to observe and sample using conventional ship-based studies. As a result, these event-driven processes remain very poorly understood. Thoroughly understanding 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 Key Scientific Questions

What is the extent, abundance, distribution, and diversity of the sub-seafloor biosphere?

Studies carried out over the past two decades have drawn attention to the presence and significance of a vast sub-seafloor biosphere within the fractured volcanic crust at mid-ocean ridges. Diverse microbial communities also exist deep within the sediments that accumulate on the seafloor during crustal aging, and within accretionary prisms along convergent margins. Recent advances in molecular techniques have found evidence for primary productivity occurring deep within both marine sediments and in the oceanic crust. Fluid-nutrient exchange between the crust and ocean lasts for tens of millions of

years and affects more than one-third of the ocean floor. Advective transfer of heat through the nearly 15,000 seamounts found in the ocean basins may drive chemically and thermally significant fluid flow in seafloor well beyond 65 million years (Figure 3.5.1). If this is true, extensive communities of microorganisms may be supported deep within the crust and sediments throughout much of the ocean basins.

At transform faults, the recent discovery of a carbonate vent system indicates that microbial communities may be linked to the exothermic, H_2 - and CH_4 -generating interaction between seawater and mantle peridotite, producing serpentinite. The associated microbiological communities are distinctly different than those associated with submarine volcanism, and represent a new biotope that does not require volcanic heat to survive. Carbonate vent systems are hosted in mantle rocks that may be exposed several tens of kilometers from volcanic centers, raising the possibility that large portions of unexplored seafloor on ridge flanks may harbor these novel alkaline, high-pH microbial habitats. Preliminary ^{14}C isotope analyses indicate that the peridotite-hosted Lost City vent field at the Mid-Atlantic Ridge has been active for more than 30,000 years.

Sediment-rich continental margins are also important submarine biotopes. Many of these environments host methane gas hydrate that is at least partly biogenic in origin. The scale and extent of microbial activity in producing and consuming methane remains unknown. The role of microbial communities in this environment is of considerable interest because estimates suggest that methane in gas hydrates deposits worldwide represent more than double the total amount of carbon in known fuel reserves. Gasses trapped in ice cores indicate large increases in atmospheric methane that may have been caused by dissociation of hydrates in sediments along continental margins. Thus, venting episodes and the transport of gasses to the sea surface and eventually into the overlying atmosphere can have a significant impact on the global carbon cycle and Earth's climate.

Each of these widely differing types of venting systems operates in an episodic manner driven by unpredictable tectonic or magmatic events. The only means of studying these systems is to install the infrastructure and sensors necessary to detect these events, and provide the capability to adaptively measure and sample remotely the changes induced by these events. The OOI will provide geoscientists with this capability.

How do submarine hydrothermal systems and their associated biological communities vary over time?

New oceanic crust is formed by episodic injection of magma into the crust. These diking/eruptive events, which may occur on time intervals of a decade or so at fast-spreading ridges, are often accompanied by the release of large volumes of hot, mineral-rich fluids into the overlying water column (so-called event plumes), dramatic changes in the chemistry of the venting fluids, and spectacular "blooms" of bacteria. The origin of these bacterial blooms is still highly speculative. A community of autotrophic thermophilic archaea adhering to the rocky walls of micro-fracture networks in the oceanic crust could experience a significant increase in nutrient supply as the heated, volatile fluids migrate upward toward the seafloor. Alternatively, these microbes could just be flushed from the sub-surface by reinvigorated hydrothermal circulation following a magmatic or tectonic event. There is little hope of conducting laboratory experiments to test these different hypotheses. *In situ* observations employing a host of different sensors and mobile platforms operating within the area affected by the event will be required to understand the origin of these bacterial blooms.

Ridge-crest hydrothermal systems can be active for years or decades in between magmatic events provided a heat source is present and a permeability structure in the upper crust allows hydrothermal fluids to reach the seafloor (Figure 3.5.3). Since the discovery of hydrothermal vents nearly 30 years ago, periodic visits to well-known vent sites along the East Pacific Rise and Juan de Fuca and Mid-Atlantic Ridges have shown systematic,



Figure 3.5.3. Black smoker chemistry measured *in situ* at a hydrothermal vent on the East Pacific Rise. *Alvinellid* worms inhabit the area closest to the high-temperature vent, with *Riftia* tubeworms at the perimeter. *Alvin* Dive 3752, 16 Jan 2002, Chief Scientist K. Von Damm. Photo courtesy T. Shank, WHOI.

long-term changes in plume flux, hydrothermal chemistry, and hydrothermal vent community structure. However, these studies have usually been limited to annual visits, at best, with much longer intervals between visits in many cases. As a result, how hydrothermal fluids and the microbial and macrofauna communities living in and around these vents vary in the absence of major tectonic or magmatic events is still poorly understood. Camera systems and *in situ* chemical sensors installed as part of a hydrothermal vent observatory will be able to characterize the variation in hydrothermal flow rates, temperature, chemical composition of vent fluids, and microbial and macrofaunal activity on time scales of seconds to decades, providing unique information on how these systems evolve over time.

What processes control the formation and destabilization of gas hydrates? What role do gas hydrates play in catastrophic slope failure?

Gas hydrate is an ice-like crystalline solid formed from a mixture of water and natural gas, usually methane. They occur in the pore spaces of sediments, and may form cements, nodules or layers. When hydrate fills the pore space of sediment, it can reduce permeability and create a trap for methane gas migrating upward from below. Through this process, highly concentrated methane and methane hydrate reservoirs can be formed. Gas from hydrate might become a major energy resource if economically profitable techniques could be devised to extract its methane.

Methane from these submarine hydrate reservoirs could significantly modify Earth's climate if it were suddenly released to the atmosphere. Methane is ~20 times as effective a greenhouse gas as carbon dioxide, and gas hydrate may contain three orders of magnitude more methane than exists in the present-day atmosphere. Because hydrate breakdown, causing release of methane to the atmosphere, can be related to pressure changes caused by glacial sea-level fluctuations, gas hydrates may play a role in controlling long-term global climate change. The formation of gas hydrate apparently cements sediment and therefore can also have a significant effect on sediment strength. The breakdown of gas hydrate may influence the occurrence and location of submarine landslides. Many slope-failure events observed on continental margins have been attributed to decreases in sediment strength associated with gas hydrate decomposition. This can represent a significant hazard to offshore structures such as oil-production platforms.

A better understanding of the processes that control the formation and destabilization of gas hydrates will require *in situ* measurements to track changes in gas hydrate content in the sediment, thermal conditions, sediment deformation, and other properties. *In situ* perturbation experi-

ments, such as placing heating elements in a borehole and measuring the response of the hydrate and host sediments to the disassociation of the hydrate, will be important in evaluating the potential effect of rising ocean temperatures on slope stability in hydrate areas and the potential for release of this methane to the atmosphere.

Role of Ocean Observatories

Understanding the linkages and feedback mechanisms among geological, fluid 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. This approach will allow scientists to detect, sample, and respond to transient events in real time. Sensors placed within areas of active flow will be able to characterize changes in flow rates, physical properties, chemistry, and microbial content of the hydrothermal fluids discharging from both high-temperature and diffuse flow systems. Work is currently underway to develop DNA-based analyses on microcomputer chips for *in situ* examination of microbial communities. These systems will not only tell us “who is there,” but also determine the composition of the communities and how the populations evolve over time and in response to events. Stationary camera systems will record the impact of these perturbations on macro-faunal populations at hydrothermal vents that can also change in response to volcanic events or longer-term changes in vent flux or hydrothermal vent fluid composition.

The value of an observatory approach in the study ridge crest hydrothermal processes has been demonstrated at NeMO on Axial Seamount on the Juan de Fuca Ridge, by the RIDGE2000 program’s Integrated Study Sites at 9°N on the East Pacific Rise and at Endeavour segment on the Juan de Fuca Ridge, and by the instrumented boreholes the ODP and IODP have established on the flanks of the Juan de Fuca Ridge (see Sidebar 3.5). A re-

gional cabled observatory in the Northeast Pacific will allow scientists to experiment remotely with, sample, and analyze a broad spectrum of geo-biological processes in settings ranging from a spreading center (Juan de Fuca Ridge) to the ridge flank (IODP Hydrogeology Transect), and from a transform fault (Blanco transform) to Hydrate Ridge on Cascadia Margin. Both the IODP and the RIDGE2000 programs have major interests in this region. The OOI infrastructure will provide unique capabilities for future studies at this site. Moored buoy observatories could be located over the RIDGE2000 ISS at the East Pacific Rise and in the Lau Basin, as well as at MARGIN study sites, such as the one off Costa Rica.



SIDEBAR 3.5. MULTILEVEL BOREHOLE OBSERVATORIES IN OCEANIC CRUST USED FOR CROSS-HOLE HYDROGEOLOGIC EXPERIMENTS

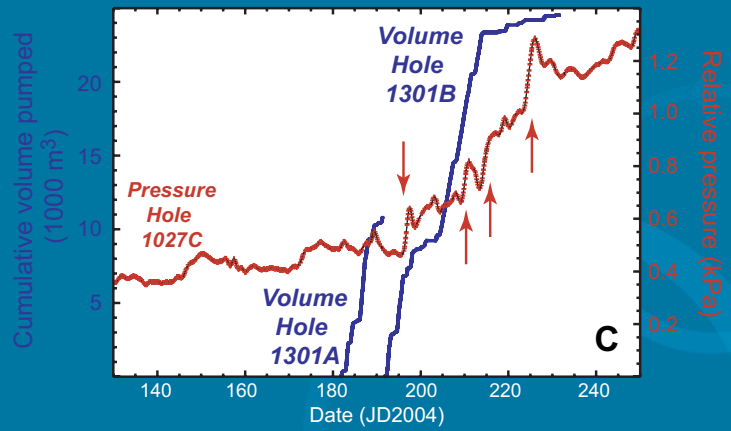
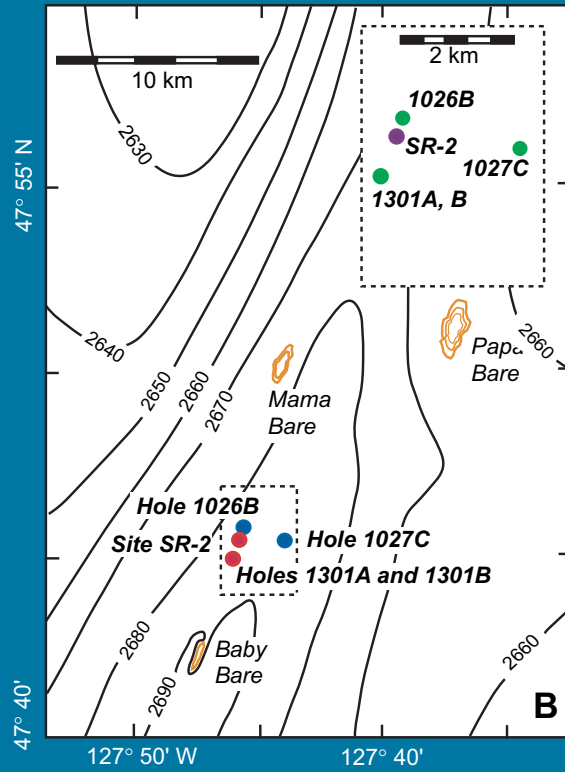
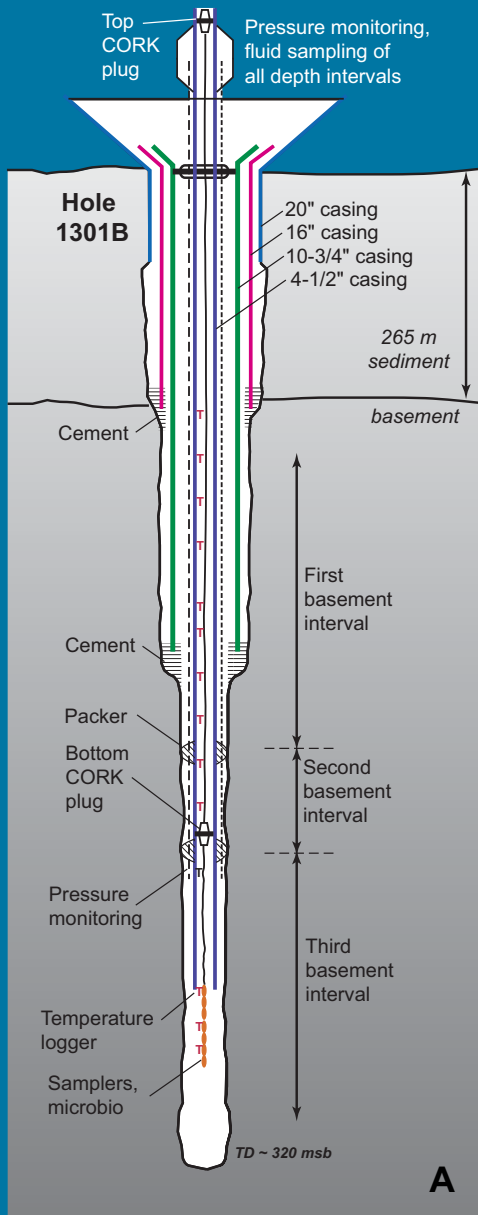
Contributed by Andrew T. Fisher, University of California, Santa Cruz; Keir Becker, University of Miami; Earl E. Davis, Geological Survey of Canada; C. Geoff Wheat, University of Alaska, Fairbanks

The upper oceanic crust comprises the largest aquifer on Earth, containing a volume of water about equal to that stored in ice sheets and glaciers. Annual fluid fluxes through the upper oceanic crust are at least as large as the global river flux to the ocean, and most of this fluid flow occurs on “ridge-flanks,” regions located far from active seafloor spreading centers. Fluid flow within ridge flanks is driven mainly by lithospheric heat rising from deep within the plate, but is influenced by seafloor and basement topography, seismic and tectonic events, and tides. This fluid circulation influences the thermal state and evolution of oceanic plates; alteration of the lithosphere and crustal pore waters; maintenance of vast sub-seafloor microbial ecosystems; and diagenetic, seismic, and magmatic activity along plate-boundary faults.

Sub-seafloor borehole observatories are now being used to investigate the thermal, chemical, and biological conditions within this sub-seafloor hydrothermal system. Integrated Ocean Drilling Program (IODP) Expedition 301 to the eastern flank of the Juan de Fuca Ridge was part of a multidisciplinary program that will elucidate the formation-scale hydrogeologic properties of oceanic crust; determine how fluid pathways are distributed within an active hydrothermal system; and reveal relations among fluid circulation, alteration, microbiology, and seismic properties. The complete experimental program will comprise two IODP expeditions, an offset seismic experiment, and long-term monitoring and cross-hole tests facilitated with submersible and ROV expeditions extending 6-10+ years after the first IODP expedition.

This hydrogeology experiment makes use of pre-existing shallow crustal Holes 1026B and 1027C. An observatory in Hole 1026B was replaced during IODP Expedition 301, and two new observatories were added in Holes 1301A and 1301B, isolating three crustal levels at maximum depths of ~320 m sub-basement (msb). During the next expedition, two multi-level observatories will be added at Site SR-2, and an observatory in Hole 1027C will be replaced. Expedition 301 borehole observatories were equipped with pressure and temperature loggers and fluid samplers to monitor multiple intervals, and growth substrate to assess microbiological activity and ecology. During the next drilling expedition, researchers will pump fluid and a mixture of inert tracers into the oceanic crust for 24 hours at Site SR-2, and monitor pressure, temperature, and chemical responses at different depths in the surrounding holes.

These observatories comprise a three-dimensional network of perturbation and monitoring points to be used during the first active, cross-hole hydrologic experiments in oceanic crust. A longer-term, larger-scale, experiment will begin when the sealed observatory in overpressured basement at Site SR-2 is allowed to vent fluid for two years (an “artesian” well test). Putting this network of borehole crustal observatories on a regional, cabled network will facilitate a new generation of active experiments, including controlled pumping (injection, extraction), tracer testing, and incubation of sub-seafloor microbes, all with real-time experimental control and data access.



3.6. Modeling and Data Assimilation

The data acquired at ocean observatories will be used in a wide range of ocean models. Models of ocean processes have evolved over the past several decades through an iterative process of formulation, testing, reformulation, and improvement. These models now encapsulate our best quantitative understanding of the physical, biological, chemical, and geological processes operating in the oceans and how they interact. For models to replicate reality in detail, they need to include observations, either through forcing fields (such as surface wind stress), or through assimilating data within the domain (e.g., by making it reproduce observed currents at a fixed point), or both (see Sidebar 3.6). ORION will depend on models to help plan observatory experiments, interpret experimental results, and make these results useful to the public. Because models are the most concise and complete representation of our state of knowledge of ocean processes, they will serve as a critical link with the IOOS and advance its ability to predict future ocean conditions.

Using Models to Design Observatory Experiments

Modeling is needed before deploying OOI sensors and platforms to help evaluate observing scenarios and simulate end-to-end observatory data flow. One obvious application will be formulating hypotheses that will be tested in focused experiments that use OOI infrastructure. A model might be used, for example, to explore the natural scales of variability that emerge from an instability and so determine the spatial and temporal scales the observatory needs to resolve to meet a particular scientific objective. This design testing can be done through OSSEs (Observing System Simulation Experiments), where prognostic model runs are sampled using different space-time schemes to understand what sampling pattern yields optimal coverage and to guide adaptive sampling strategies. Furthermore, the OSSEs can be used to

make informed cost-benefit analyses so that the limited observatory resources can be used in optimal ways given realistic budget constraints.

Using Models to Extend Observations

Despite the dramatic increase in observational data associated with observing programs such as OOI and IOOS, the ocean will always be under-sampled. Models containing a proper representation of the ocean, when assimilating data (that is, constraining the model to reproduce observations where and when they are made), can supplement and extend observatory data that are necessarily limited in space or time. For example, the highly variable surface flow field is an integral part of harmful algal bloom development, but it is sampled in an experimental area by a finite number of current meters. How well these measurements represent the true field depends on the ability to resolve the natural scales of variability. Statistical approaches for interpolation can estimate information between measurement sites in a manner that is the best possible given known statistics, but they do not normally include information about the known dynamics of the flow field. A data-assimilating model can, on the other hand, provide a dynamical interpolation that takes advantage of the known physical laws expressed by the model. With either the statistical or dynamical approach, it is possible to estimate errors in the interpolations, hence quantify how well a given piece of estimated information is known. Whether the statistical or dynamical approach yields better results in a given situation presently depends on the circumstances (such as knowledge of the governing laws or on data density), but the dynamical approach in principle can ultimately provide a better estimate of the field while furthering scientific understanding.

The OOI will be a multi-scale observing system. Information on global and regional scales is required to force coastal models, for example. At the same time, information needs to propagate from smaller scales (regional and

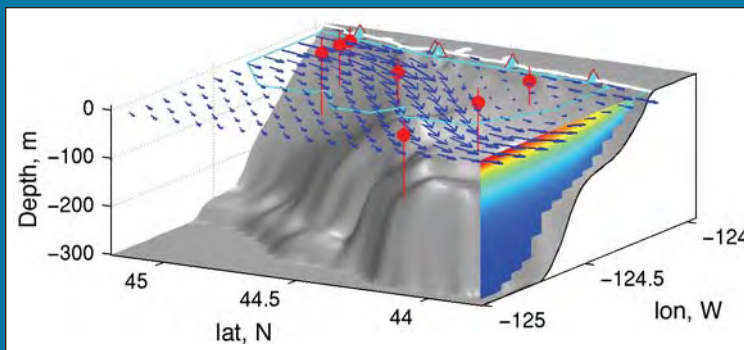
SIDEBAR 3.6. SCIENTIFIC CAPABILITIES OF DATA-ASSIMILATING MODELS

Contributed by J. Barth, Oregon State University

No observational system can measure all of the important oceanic variables with sufficient temporal and spatial resolution to determine the huge range of physical, chemical, and biological phenomena. Data assimilation is a powerful, versatile methodology for estimating oceanic variables. The estimation of a quantity of interest via data assimilation involves combining observational data with the underlying dynamical principles governing the system under observation. The melding of data and dynamics is a powerful methodology, which makes possible efficient, accurate, and realistic estimations that might not otherwise be feasible.

Numerical coastal ocean circulation models may be combined with a wide range of observations ranging from properties at the ocean surface obtained with tide gauges, satellites, or land-based remote sensing (sea level, temperature, velocity) to measurements obtained in the water column with moorings or autonomous vehicles (velocity, temperature, salinity). Recently, surface velocities measured with land-based coastal radar arrays have been assimilated into numerical coastal ocean circulation models, enhancing the study of flow-topography interactions in the coastal ocean. For example, measured surface velocities

were used to estimate properties of the internal lunar semi-diurnal tide that arises from interaction of the depth-averaged lunar semi-diurnal tide with continental shelf topography. The internal tide consists of large, opposing currents in the surface and bottom layers of the coastal ocean and has important consequences for mixing and for larval transport across the continental shelf. Because the internal tide is generated by flow interaction with sometimes small-scale topography and relies on the presence of time-varying ocean stratification, it is a very difficult problem to tackle with observations alone. By extending the more easily measured surface velocity fields into the ocean interior, the data-assimilating model can be used to detail the dynamics of the interior velocity and thermohaline fields. In particular, the spatial distribution of near-bottom flows can be used to estimate frictional dissipation within the bottom boundary layer and upwelling out of that same layer. These processes have important consequences for shelf ecosystems.



Elements of a coastal ocean observatory off central Oregon. Data from moorings (red), and land-based radar measurements of surface velocity (cyan), are combined with a coastal ocean circulation model to investigate flow interaction with a subsurface bank. Depth in meters; colored vertical section indicates ocean temperature (blue is cold). Figure courtesy of A. Kurapov, Oregon State University.

coastal) to the global scale because the global observatory will be unable to provide refined information in all settings. Thus, well-resolved regional-scale information can be used to test how well basin-scale models treat sub-basin scales (Figure 3.6.1). Models will thus be an integrating tool that quantitatively conveys this multi-scale information among observatory components, to users and to the public at large.

Model Nowcasting

Models using ocean observatory data can produce real-time analyses, sometimes called “nowcasts.” Nowcasts provide a high-quality estimate of the ocean’s present state, and so open up new approaches to data interpretation. For example, four-dimensional (three spatial dimensions plus time) models can provide otherwise unavailable perspectives of different physical, chemical, or biological properties that help scientists and educators comprehend relations among ocean properties. Further,

having four-dimensional information allows scientists to estimate how critical quantities vary and so they can diagnose quantitatively why a given change is occurring (Figure 3.6.2). More creative uses of model results may include a “virtual reality” representation of the measured field, an approach that will allow an investigator to explore the data set interactively, in order to achieve new insights that might have otherwise gone unrecognized.

Nowcasting models can also provide an organized, integrated view of multiple data sets. This coherent summation makes them a particularly useful tool to expedite data mining and for studying the interrelationships of observed information. Finding information on, say, modeled chlorophyll fields will then make it easy for the user to find related physical information (currents or frontal locations) or linked chemical or biological fields (nutrients or predator populations). This unifying capability will ultimately need to be closely integrated into the overall OOI cyberinfrastructure capability.

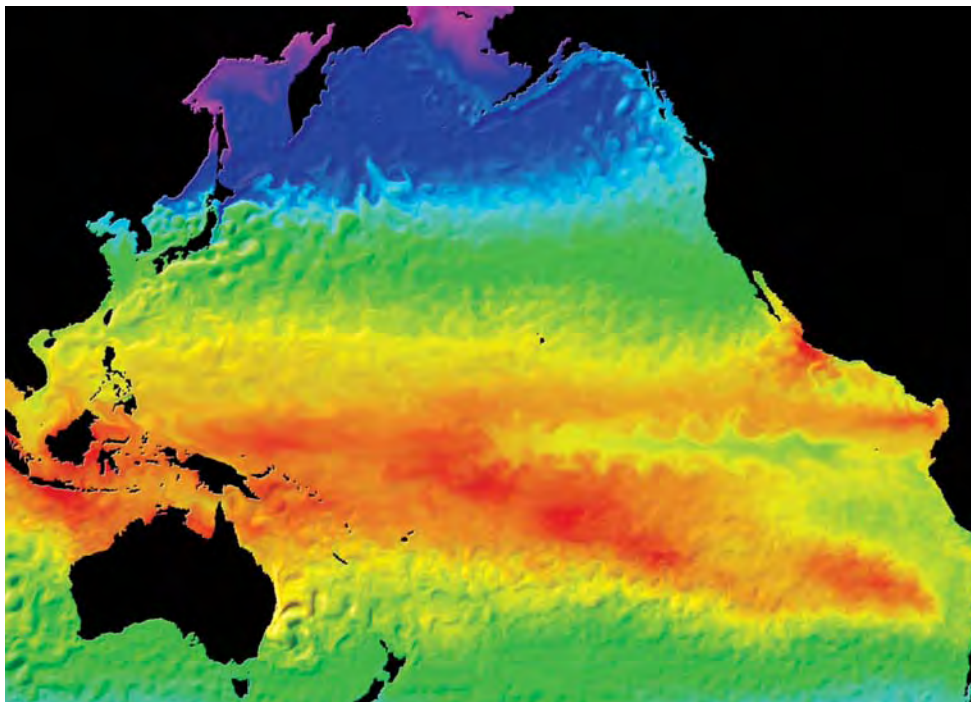


Figure 3.6.1. A snapshot of sea surface temperature (in color) with shaded relief to indicate variations in sea-level slope. This simulation was produced using a high-resolution (12.5-km) Pacific Ocean general circulation model. Models that can represent all scales are essential for integrating data collected from the global, regional, and coastal OOI observatories. Figure courtesy of Yi Chao, Jet Propulsion Laboratory.

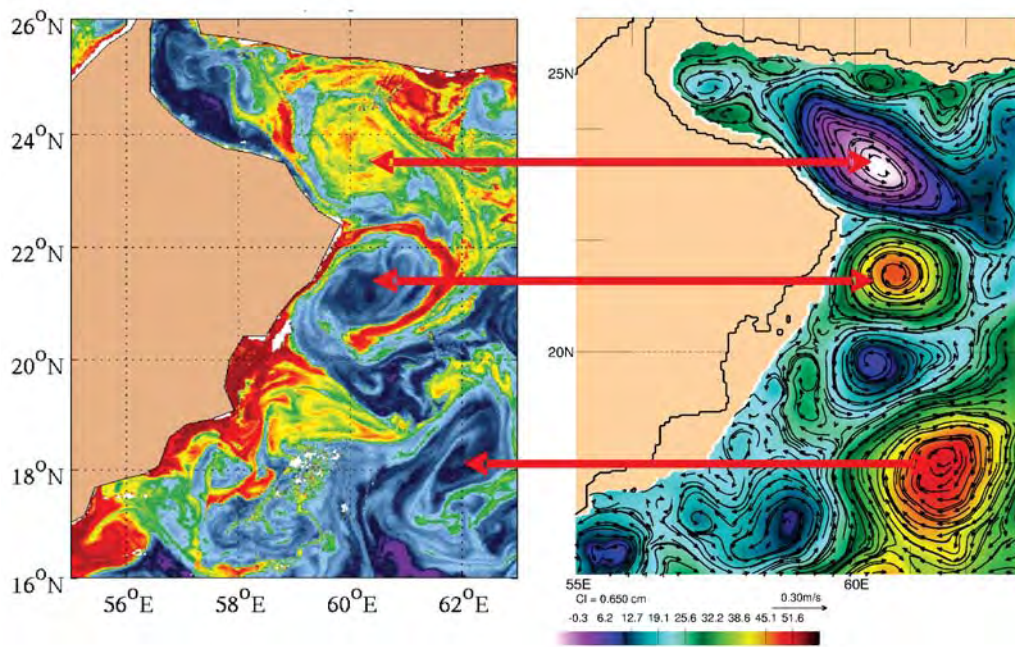


Figure 3.6.2. A composite of chlorophyll concentration (indicated by color) from the SeaWiFS satellite over September 30 through October 7, 2002 shows high-concentration plumes extending from the Arabian peninsula to the deep ocean (left). A numerical ocean model assimilating sea-surface-height observations provides the ocean circulation and indicates that some of the filaments are advected into the deep waters by mesoscale eddy features (right). The color in the model result indicates the sea-surface height; the vectors are the surface currents. Assimilative models help provide context for the OOI observations. Figure courtesy of Gregg Jacobs, Naval Research Laboratory.

Model Forecasting

Initialized by model nowcasts, models can be integrated forward in time to produce ocean forecasts, similar to the weather forecasts routinely conducted for the atmosphere. Forecasting is a powerful scientific tool because each forecast is essentially a hypothesis based on the observations and the knowledge embedded in the model. If the forecast succeeds, it means that the observational input (including forcing fields, boundary condition information, and assimilated data) and model formulation are likely to be valid. If the forecast fails, the scientist is challenged to find out why, and so ultimately improve understanding of the underlying processes. The result could be as simple as refining estimates of model input parameters, or as far-reaching as discovering new and better representations of the parameterizations, rates, and governing principles incorporated into the model. Predictions are also valuable for designing future experiments and determining when critical measurements should be made.

The implications of forecasting go beyond its considerable significance as a scientific tool. Forecasting is of essential practical value. For example, improved ocean forecasting of circulation and waves will ultimately lead to better weather and tsunami predictions, search and rescue operations, and response to pollution events. These improved forecast models and procedures will be one of the most important ocean observatory contributions to ongoing enhancements in IOOS capabilities.

Models of all forms, whether or not they assimilate data, help integrate knowledge. Ocean observatory models will incorporate observed information, integrating diverse, interdisciplinary data sets and so provide answers to problems that would be difficult or impossible to address without the availability of dynamically interpolated information. Finally, models can provide a powerful tool for summarizing and communicating results to scientists, educators, or the general public (see Chapter 5).

3.7. Interactions Between Science and Technology in Ocean Observatories

Throughout the history of science, and especially in the geosciences, the interaction between science and technology has been mutually reinforcing. In many instances, changing or evolving scientific queries provide the impetus for new technology development. A prominent and recent example is the human genome project, whose progress has accelerated dramatically in response to advances in DNA mapping technology for which it has been the principal driver. In the ocean sciences, development of, and improvements in, conductivity-temperature-depth (CTD) and acoustic current measuring technologies are largely responses to the needs of the physical oceanography community for more rapid, reliable, and economical measurements of water-column properties.

The ocean sciences are marked at least as frequently by the introduction of new technology that, in turn, drives science in new directions. In some cases, such innovations are the direct product of development within the community, but in most instances new methodology is imported and adapted from other fields as opportunities are identified and recognized by forward-looking individuals. A prominent example is the introduction of modern time series and spectral analysis methods from the statistics and electrical engineering disciplines beginning in the 1950s. These techniques have transformed geophysics and physical oceanography from qualitative to quantitative fields; geoscience requirements are, in turn, driving new developments in time-series analysis.

A second example is the development of data assimilation and modeling techniques in the 1980s, which are the product of dramatic increases in computer speed and size driven by the nuclear weapons design community combined with broad-based improvements in numerical methods. Data assimilation techniques (see Sidebar 3.6) have transformed the way in which physical

oceanography experiments are carried out, and operate synergistically with new float-based observational systems. Their impact is only beginning to be felt in other fields of oceanography.

The Impact of Ocean Observatories on Technology

The introduction of the family of technologies that enable ocean observatories will be transformational for both ocean scientists and ocean engineers. There are four principal areas in which this is already occurring, and in which the trend can reasonably be expected to accelerate as the OOI is implemented: (1) understanding the design and implementation of remote, reliable, self-controlling undersea hardware; (2) developing the software elements (cyberinfrastructure) necessary to manage sensors, data, and the physical infrastructure; (3) galvanizing the development of the mobile platforms necessary to extend ocean observatories from point to areal coverage; and (4) driving the design of new sensors required to answer evolving science questions. None of these developments will occur coherently or rapidly in the absence of the unifying focus from ocean observatories, yet all will be required to make them continuously successful through the life cycle of the ocean observatory paradigm. Each area will empower the ocean sciences community to move in new directions. Finally, each area will either stimulate parallel progress or spin-off new concepts for a variety of commercial and governmental applications where reliable, real-time access to heterogeneous sensor networks is required.

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 diverse commercial and government systems have been built that achieve some of the required engineering goals, none approaches the level of complexity of an ocean observatory system. For example, NASA has been highly successful at launching sophisticated satellites on planetary missions for several decades, but these are designed as integrated sensor platforms with well-defined, fixed requirements unique to a specific mission. The submarine telecommunications industry builds extremely reliable undersea hardware to facilitate high-bandwidth data transport among a small number of fixed terrestrial terminals, but has not grappled with the issues of power or communications delivery at distributed points on the seafloor. NOAA has long operated autonomous surface weather buoys in hostile parts of the ocean, but with the exception of a small number of tsunami warning buoys, their mission does not require connections to sensors on the seafloor. An emerging change within the oil industry will transition operations from manned surface to autonomous sub-surface platforms as the depth of offshore oil fields increases. The requirements these new systems must meet have considerable overlap with those governing ocean observatories, and are the only analogous systems under consideration.

Thus, ocean observatories represent a substantial ocean engineering technological leap rather than an incremental extension of current practice. The history of the ocean sciences is replete with instances where large changes in technological capability enable new science and, in turn, galvanize new technology development. Ocean observatories will not be an exception.

Ocean Observatory Cyberinfrastructure

While the hardware engineering difficulties of ocean observatories are substantial, implementing a software framework within which they can operate also poses a significant challenge. Devising the cyberinfrastructural glue that will seamlessly bind sensors and actuators, un-

dersea infrastructural systems, dry data servers and archives, and human or machine end users together represents an essential integrating element of a working ocean observatory and a cutting-edge information technology research topic.

The seamless linking of loosely coupled, distributed resources (e.g., the grid) is a rapidly growing information technology paradigm shift. The grid concept provides a unifying framework for ocean observatory cyberinfrastructure, but will require a number of significant extensions to produce a fully functional system. As for the hardware elements, prior or ongoing work has addressed some key aspects. For example, the astronomy community has initiated the National Virtual Observatory (NVO) project whose objective is enhancing access to astronomical data and computing resources. The NVO is developing tools that make it easy to locate, retrieve, and analyze data from distributed archives and catalogs, and to compare theoretical models and simulations with observations. These are critical aspects of an ocean observatory cyberinfrastructure, but do not include real-time data flow, infrastructure control, or a high diversity of data types. Other projects (e.g., the Common Instrument Middleware Architecture effort at Indiana University) are extending the grid framework to include instrumentation as an integral element.

No prior project has addressed autonomous management of infrastructure, nor has any group attempted to bind all of these elements together into a working system. Finally, the development of ocean observatory cyberinfrastructure will not be a single-step engineering effort, but rather will continue throughout the life cycle of ocean observatories driven by a combination of continuing progress in information technology and changing requirements in response to an evolving experience base and newly emerging scientific questions. In fact, the physical infrastructure of ocean observatories will serve as a testbed for cyberinfrastructure development on an ongoing basis.

Mobile Platform Development

Whether buoyed or cabled, fixed ocean observatory infrastructure will provide only a point (or perhaps multi-point) scientific presence on the seafloor or within the water column. *In situ* remote sensing methods, for example, acoustic tomography, can provide some data between fixed and mobile platforms over large ocean areas and volumes (Sidebar 3.7). However, direct and more detailed spatial sampling poses significant additional technological challenges. 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 element of this extension. Ocean observatories will stimulate engineering innovation in autonomous vehicles, whether powered or free-floating. For example, current-generation 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 *in situ* power source, improvements in vehicle reliability (which pose a wide range of control, mechanical component, and corrosion issues), 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 not presently operational.

A connectionless communications system that can maintain contact with a moving platform would be even more enabling. Acoustic communications at low bandwidth over ranges of a few kilometers is currently feasible, but the 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 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. Figure 3.7.1 presents a concept for such a system. At the same time, the introduction of mobile platforms that are integrated into the ocean observatory infrastructure would be enabling for both

science and education purposes. Platforms that can be remotely commanded to investigate episodic events are 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 node. Further, linking imagery from and providing control for AUVs to users in real-time can have a substantial impact on the public perception of the deep ocean, and has profound educational applications.

Sensor Development

Ocean observatories will transition an increasing amount of ocean science from sample-recovery-based to *in situ* measurement protocols that are the only effective way to obtain temporal information that can be correlated with a contemporaneous ocean observatory data base. In some disciplines, sensor technology is relatively advanced; for example, seismic sensors with noise levels below ambient and with very wide-band 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 time scales, 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 functionality only in a laboratory environment to operation in a remote, hostile one, and will in turn empower new directions in *in situ* biology (Figure 3.7.2). A

SIDEBAR 3.7. OCEAN ACOUSTIC THERMOMETRY IN THE NORTH PACIFIC OCEAN

Contributed by Bruce Howe, University of Washington/Applied Physics Laboratory

The oceans are by a huge margin the largest heat reservoir in the global climate system. This has led to the characterization of the oceans as the “flywheel of climate.” A major goal of basin-scale acoustic thermometry is to obtain high-precision estimates of average heat content and temperature. Acoustic thermometry measures ocean temperature within an ocean volume by transmitting sound through it. The advantage to using acoustic methods to measure basin-scale variability is the inherent integrating nature of the acoustic transmissions. Ocean-basin-scale transmissions provide horizontal and vertical averages that reduce noise due to smaller-scale ocean variability, providing precise measurements of basin-scale heat content. Further, acoustic measurements can be rapidly repeated at low cost, once the measurement system has been installed. On a global basis, the estimation of long-term heat flux with an accuracy of a fraction of a W/m^2 over the period of a year is a realistic goal.

A prototype ocean acoustic observatory has been measuring large-scale, depth-averaged temperatures in the North Pacific Ocean for the past nine years. The geometry is shown in the figure, together with the measured time series for two of the acoustic paths. For comparison, travel times computed from an ocean model assimilating satellite altimetry data (higher heat

content raises sea level), are also shown. Even at long temporal and spatial scales, the ocean is highly variable. A path from Kauai to California shows a modest cooling trend (longer travel times) until the present time. On the other hand, a path to the northwest showed modest warming and a weak annual cycle from late 1997, when the transmissions started, until early 2003, when the path cooled abruptly and a strong annual cycle returned. These changes stemmed from the warming of the central Pacific that occurred in this interval. Comparisons between measured travel times and those predicted using ocean models, constrained by satellite altimeter and other data, show significant similarities as well as substantial differences, indicating that acoustic travel times will provide significant constraints on the large-scale variability in ocean models.

The accurate measurement of basin-scale temperature to high accuracy is essential for detecting and measuring the impact of large-scale oceanographic variability, such as the Pacific Decadal Oscillation and North Atlantic Oscillation, on climate to understand the magnitude of anthropogenic forcing. Heat content, tied directly to changes in sea level, is also essential for understanding the component of sea-level rise that can be tied directly to temperatures induced by global warming. Acoustic

thermometry would supplement the local time series measurements at the moorings in the Global Ocean Observatory with time series of average ocean temperature between the moorings.

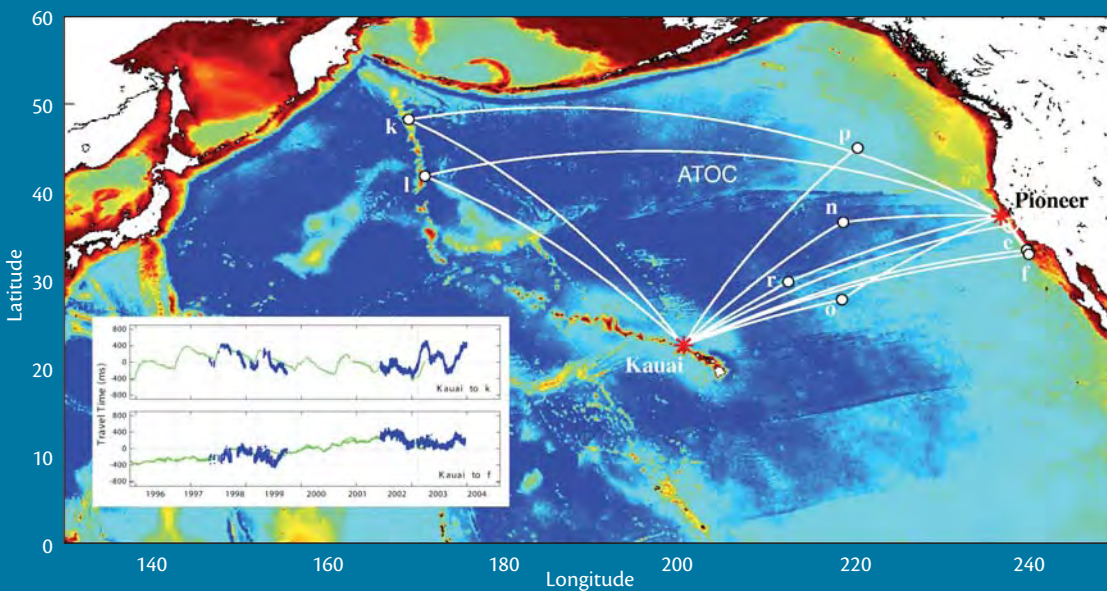


Figure 3.7.1. Cartoon depicting an autonomous underwater vehicle (ABE) optically linked to a modem that provides real-time, high-bandwidth, two-way communications. By installing networks of such modems that operate analogously to a cellular telephone system and that are linked to an ocean observatory, autonomous vehicles can be interactively operated over areas of the seafloor or volumes of the ocean. Figure created by Paul Oberlander, Woods Hole Oceanographic Institution.

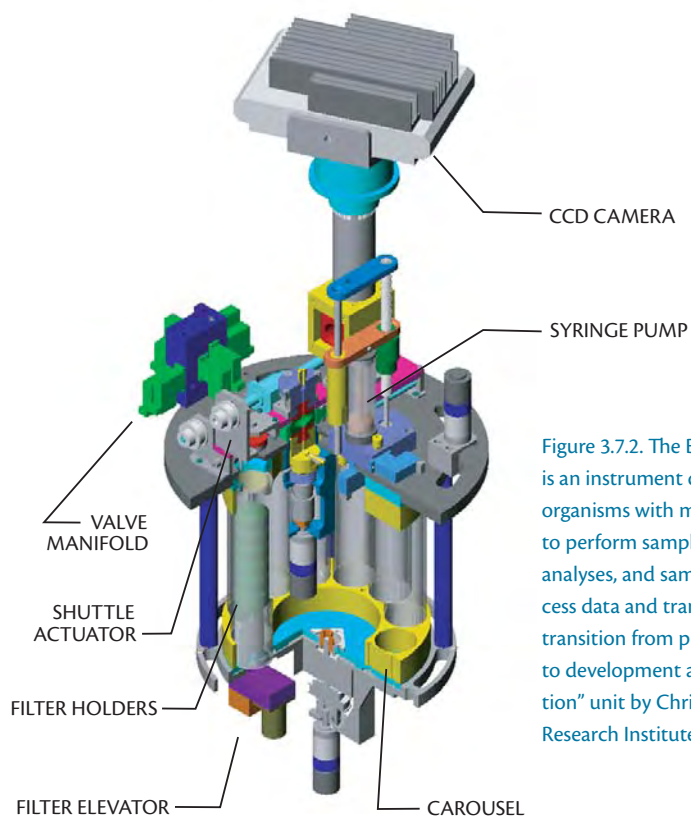
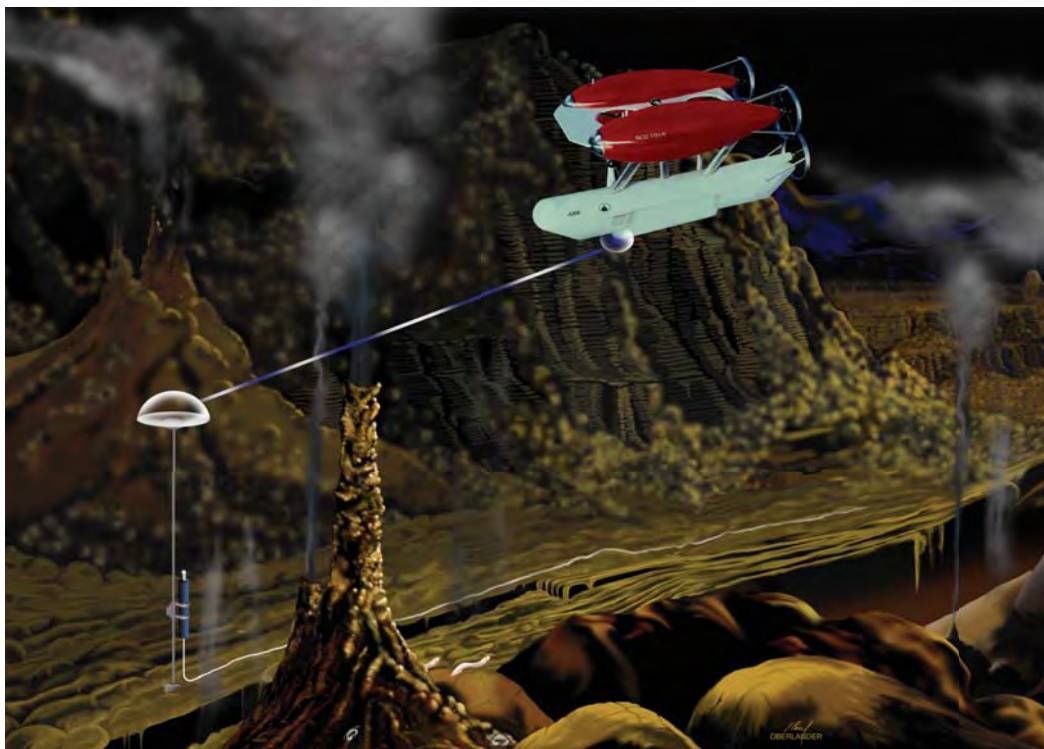


Figure 3.7.2. The Environmental Sample Processor (ESP) is an instrument developed to detect multiple microorganisms with molecular probe technology, as well as to perform sample collection, concentration, different analyses, and sample archival. The system will also process data and transmit results. The ESP is in a period of transition from prototype and short-term deployments to development and application of a “second generation” unit by Chris Scholin, Monterey Bay Aquarium Research Institute.

list of sensors needed or wanted for ocean sciences would be virtually endless, and in many instances, sensors will evolve which cannot be envisioned in the present. This is especially true in areas that span disciplinary boundaries.

Technology Spin-Offs

Spin-offs in the academic, commercial, government, and military sectors can reasonably be expected to ensue from all of these aspects of ocean observatories. For example, research ocean observatories will provide new sensors and observation technologies that can eventually be transitioned to the IOOS operational network. The synergy between the requirements for research ocean observatories and next generation oil field infrastructure has been noted, and deserves further exploitation and collaboration. Similarly, the cyberinfrastructure required for ocean observatories is inherently at the leading edge of information technology research, and will certainly produce commercial applications in the future. Many of the technologies required for ocean observatories have obvious application in military or intelligence surveillance. Evolving, *in situ* sensor technologies required for ocean observatory science will also be essential elements of future environmental monitoring and homeland defense systems. In each of these areas, the interface between wide applications and the ocean observatory science community is primarily technological. However, the ongoing synergy between science and technology is the essential driver of improvements, and hence serves as the innovation engine underlying the ocean observatory paradigm.

CHAPTER 4. ENGINEERING ELEMENTS

Ocean observatories may be designed around either a surface buoy containing an autonomous power source and a wireless (e.g., satellite) communications link or a submarine fiber optic/power cable connecting one or more seafloor science nodes to the terrestrial power grid and communications backhaul. As described in Chapter 2, these two types of observatories may be used interchangeably in coastal observatories, while they are the principal technological foci of the global and regional cabled observatories, respectively.

Surface moorings are a mature and reliable technology, and satellite data telemetry from surface buoys and ships has become routine. Their connection to sensors on the

seafloor is more problematic, but to be useful in ocean observatory applications, they must operate reliably over periods of years, must be serviceable from UNOLS or international-partner vessels, and must be cost-effective. Acoustically linked surface moorings that do not deliver power to the seafloor (Figure 4.1) provide low-bandwidth (up to 30 kbit/s) connectivity. Single-point moorings tethered with electro-optical-mechanical (EOM) mooring cables and using surface following buoys (Figure 4.2) can provide seafloor power (about 100 W) from the buoy and can link data at maximum satellite connectivity rates. Large tri-moored spar buoys (Figure 2.3) that respond primarily to low-frequency wave motions are a complementary approach to the EOM-tethered single-

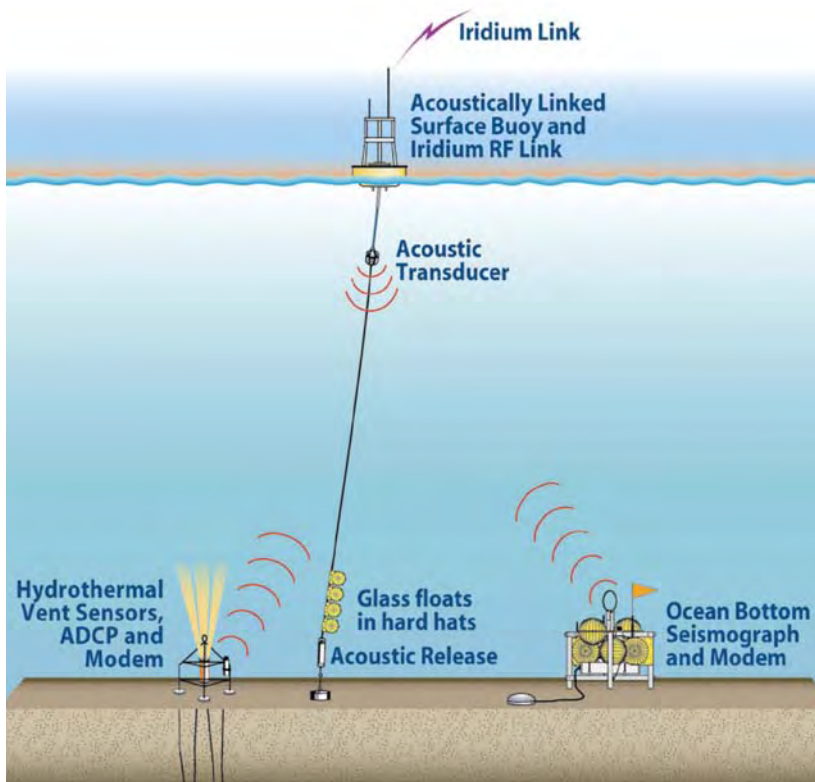
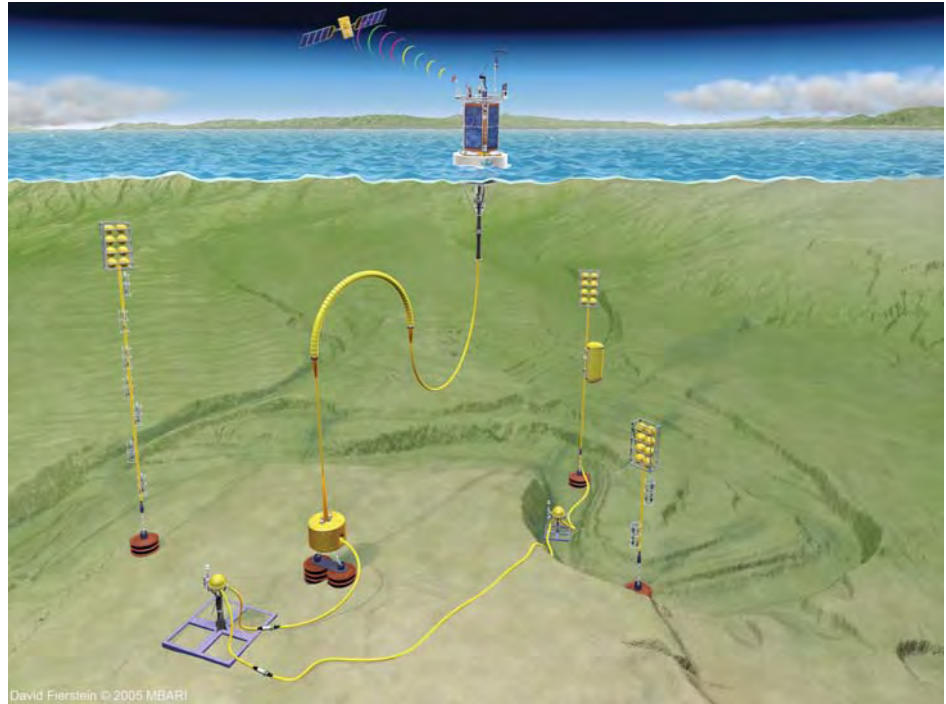


Figure 4.1. Cartoon showing an acoustically linked surface buoy that communicates with a set of autonomous instruments on the seafloor that uses acoustic modem technology. The buoy is linked by satellite to shore. Figure courtesy of Dan Frye, Woods Hole Oceanographic Institution.

Figure 4.2. Cartoon showing a surface discus buoy connected by an electro-optical-mechanical (EOM) s-tether cable to a series of science nodes on the seafloor. The buoy provides power and a communications link to the science nodes, which in turn serve a series of instruments that plug into them. The surface buoy is linked by satellite to shore. Figure courtesy of Monterey Bay Aquarium Research Institute.



point design and can provide substantially more power (up to 1 kW) from diesel generators located in the spar buoy. Acoustically linked surface moorings do not require the development of new mooring technology. The major challenge for the EOM tethered designs is designing a cable that provides adequate mooring compliance without damaging the conductors and optical fibers from bending strain, and that has a size, weight, and cost compatible with operation in strong current regimes and with small surface buoys. This is an area of active current research, and a range of solutions appears to be feasible.

Over a hundred years of development of submarine cables for the telecommunications industry has resulted in highly reliable commercial-off-the-shelf (COTS) products. The design requirements for an ocean observatory cable are highly compatible with the standard capabilities of telecommunications cable. Cable-based installations such as the regional cabled observatory depicted in Figure 2.4 can provide much greater amounts of power and

bandwidth for instruments than can buoys. Tens to hundreds of kilowatts of power and 10-100 Gb/s or more of data can be delivered to cabled observatories over COTS submarine telecommunications cables.

Ocean Observatory Infrastructure Elements

Whether a system is buoyed or cabled, most science users will connect instruments at a seafloor node that contains the electronic subsystems necessary to provide power, communications, and control functions for both infrastructure and sensors, along with a wet-mateable connector to which instruments may be connected. Two examples of seafloor nodes are shown in Figure 4.3; both designs allow the node to be recovered by a research vessel for repair or servicing.

A simple physical block diagram (Figure 4.4) shows the key hardware subsystems of a cabled observatory science node. Copies of these subsystems appear both in other

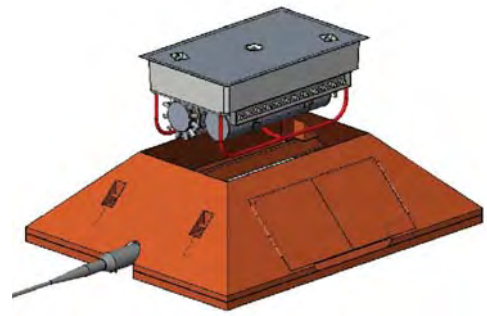
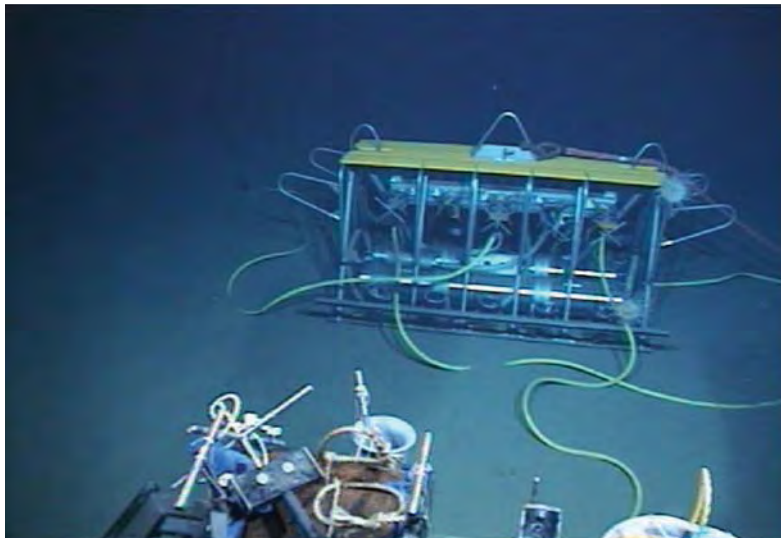


Figure 4.3. Two concepts for the design of a seafloor science node. The photograph (left) is the Hawaii-2 Observatory junction box that was installed in 1998 about halfway between California and Hawaii in 5000 m of water. The junction box consists of two electronic pressure cases at the bottom and an oil-filled wet-mateable connector manifold at the top. The entire unit is constructed of titanium for corrosion protection and is designed to be unplugged from the submarine cable to which it is connected and recovered for servicing. The cartoon (top) shows the concept for the Monterey Accelerated Research System (MARS) science node to be installed in late 2005. All of the electronic systems on the node are contained in a removable unit that is designed to be unplugged and recovered with a remotely operated vehicle. Figure courtesy of Alan Chave, Woods Hole Oceanographic Institution.

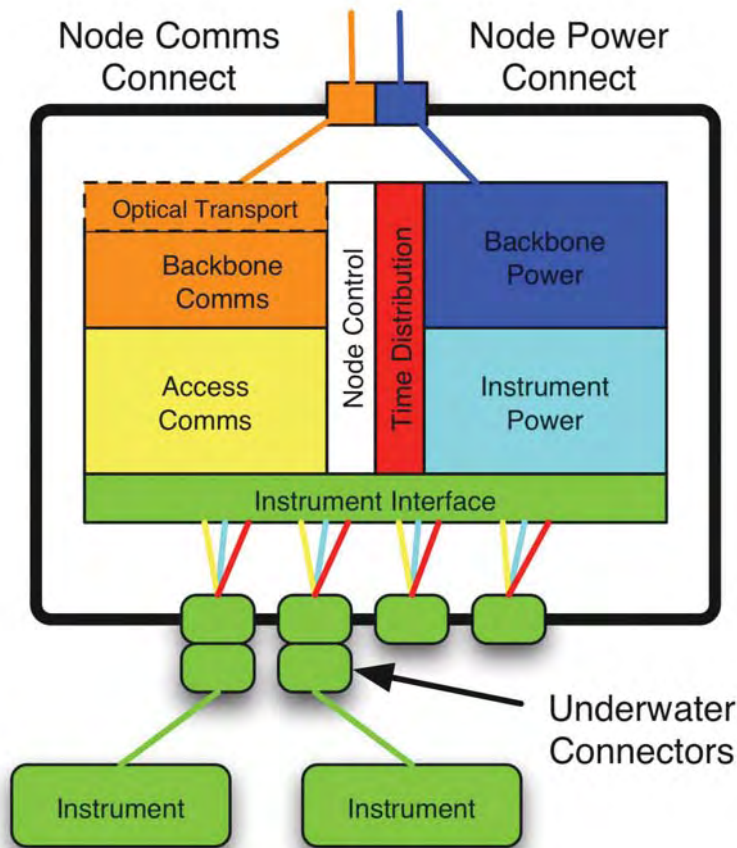


Figure 4.4. Block diagram showing the main seafloor science node subsystems. Figure courtesy of Alan Chave, Woods Hole Oceanographic Institution.

science nodes (if present) and in a shore station. While the figure is directly pertinent to a cabled observatory, the same subsystems will appear in a buoyed installation except that the submarine cable is replaced by the combination of a buoy-to-satellite communications link and an autonomous power source in the buoy. The remaining subsystems will still be present in the seafloor science node, although their power and bandwidth capability may be more limited. Analogs to the node subsystems will exist in a buoy, although it may be prudent to operate as many of the control functions as possible in proxy mode on shore, depending on the implementation.

The main subsystems in an ocean observatory science node handle power, data communications, observatory management, and time distribution. Each of these may be subdivided into a hierarchy of sub-subsystems or beyond; the first sub-level is depicted for some elements in Figure 4.4.

The power subsystem transforms the high voltage (up to 10 kV) carried by the single conductor (with seawater return) present in fiber optic cable to lower levels usable by both the node infrastructure and science users. Normally, this transformation will be accomplished in two stages for a cabled observatory, with the backbone power stage converting the line voltage to a medium level and the user power stage providing isolated standard voltages to user loads. For a single node cabled or buoyed observatory, a power system of this sort with simple monitoring and telemetry will probably suffice. As the number of nodes grows on a multi-node cabled observatory, issues of power monitoring and management increase in complexity.

The data communications subsystem serves two key purposes: aggregation of data streams from many sensors around a science node, and routing/repeating on the high-speed backbone optical network. Anticipating that future ocean observatory instrument data will consist primarily of Internet protocol (IP) packets, the access communications block can be implemented using an Ethernet switch that transfers data to the backbone com-

munications subsystem. Ethernet is available at standard data rates of 10 and 100 Mbit/s and 1 and 10 Gbit/s, and these are expected to increase over time.

For a single node cabled or buoy observatory, the backbone communications/optical transport sub-subsystems can consist of a high-speed Ethernet switch with single channel optical transport. For multi-node ocean observatories, the backbone communications functions can be implemented in one of several ways, depending on the optical transport protocol and network physical topology. For a mesh network, which constitutes the most efficient way to increase network reliability for a given number of nodes, the most general approach would use a high-speed version of Ethernet using multiple independent optical transport channels, with the number depending on the desired total data rate.

Time distribution can be provided by Network Time Protocol, which is a widely used protocol that can serve time at an accuracy of a few milliseconds across simple networks. It can serve as a primary time standard suitable for most instruments on a cabled ocean observatory. Higher-accuracy (e.g., order 1 μ s) synoptic time can be served to science users using a separate system as shown in Figure 4.4

The remaining science node subsystems in Figure 4.4 provide specialized functions that are actually elements of a comprehensive observatory management system comprising the data management, node control, and instrument interface subsystems. The node control subsystem provides high-reliability oversight of all node functions, including telemetry of critical data and master control of key subsystems. It may be distributed among the other node subsystems or centralized, depending on the implementation. The instrument interface subsystem provides power, communications, and time services to instruments and sensors, and may be physically distributed between the science node and individual instruments. It may also provide critical data-management functions such as storage and service of metadata, and contains part of the seafloor component of the

data management subsystem that is logically distributed throughout the observatory. The hardware elements of the observatory management system shown in Figure 4.5 are intimately linked to an overarching ocean observatory cyberinfrastructure that automates most observatory management functions.

Cyberinfrastructure for Ocean Observatories

The functional block diagram in Figure 4.5 shows the key cyberinfrastructure processes required to implement the observatory management system.

An instrument process resides logically between the instrument and the access data and user power connections at the node. Some of its functions include: monitoring and control of power to the instrument; instrument ground fault detection; bi-directional transmission of data to/from other instruments, other nodes, and the shore station; storage and forwarding of instrument metadata as required; and acquisition and processing of synoptic time. The instrument process may physically reside in the instrument itself, in the node between the wet-mateable user port and the node data/power

hardware, or even in proxy mode on shore or in a buoy, depending on how the software implementing the user process has to interact with the hardware making up the ocean observatory.

The node-control process may interact with hundreds of instrument processes and with several shore-based processes. A partial list of the node-control process functions includes: monitoring and control of the node power buses; monitoring and control of the node data communications system; and collection and transmission of node engineering data. The node-control process may reside physically in the node or on shore/in a buoy.

An ocean observatory operations center on shore contains all of the processes to monitor and manage the myriad components of an ocean observatory. The operations center connects to a set of distributed data archives, which are probably not collocated. There are four main types of shore-side processes: the communications-control process, the power-control process, the data-buffering process, and the data archive process.

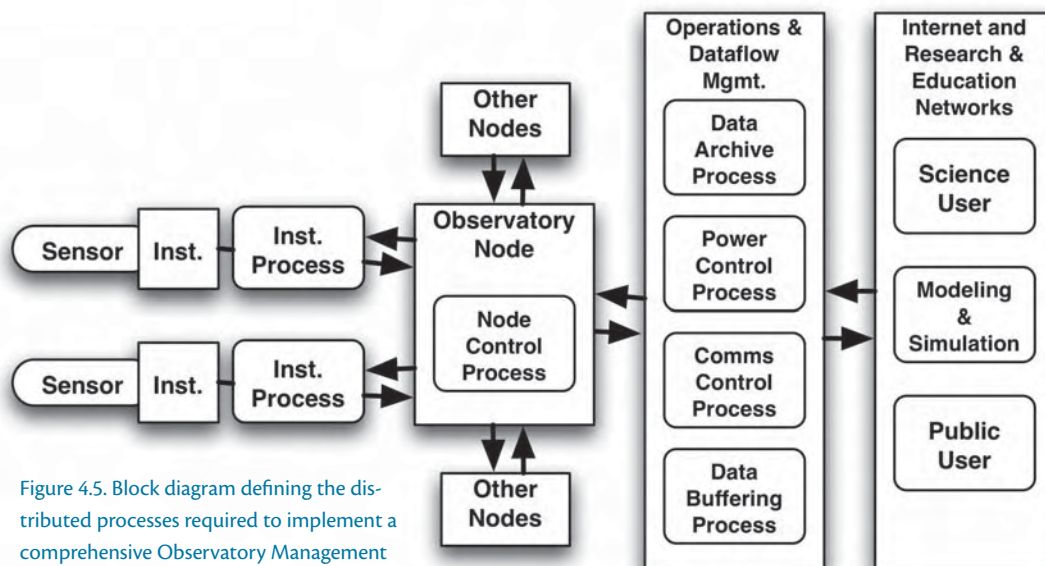


Figure 4.5. Block diagram defining the distributed processes required to implement a comprehensive Observatory Management System that comprise the major elements of an ocean observatory cyberinfrastructure. See text for discussion.

The communications and power control processes are used by ocean observatory operators or users to control various node, instrument, and sensor functions, and may interact with both the node control and instrument processes. A partial list of their functions includes: monitoring and control of system-wide power usage and availability; monitoring and management of system-wide data bandwidth usage and availability; and creation and elimination of connections between instruments or nodes and other processes.

The data-buffering process gathers real-time data (and instrument metadata) from all instruments and provides a short-term buffer in the event that connectivity is interrupted for any reason. Data-archive processes gather and receive data and metadata from specified instrument. Different repositories may receive and process data from different types of instruments. A partial list of the data-archive process functions includes: extraction of instrument metadata from the instrument processes as required; flagging metadata state change; acquisition and post-processing of data streams from instrument processes; and possibly provision for national security control over data access.

While many of the processes described above could be implemented in hardware, a key characteristic they share is the need for repetitive, automatic, inter-service communication and the concomitant exchange of data or commands. In addition, it is likely that the processes needed to operate an ocean observatory will evolve over time as unforeseen modes of operation develop and users and operators build an experience base. Evolving uses argues strongly for an implementation that places hardware interfaces at primitive levels in the subsystems and implements the inter-process links and their control in software which can be remotely modified as required. This implementation process is especially needed for a seafloor installation where changes of hardware are extremely expensive. Finally, as ocean observatories proliferate, the need for interoperability will become increasingly important, especially at sensor and user interfaces; however, interoperability at the internal levels of ocean observatories

will lead to a reduction in operating costs as the community-wide experience base grows. If all of these interfaces are well defined, then the internal workings of instruments or infrastructure become irrelevant to most users.

The preceding description contains the essence of a loosely coupled, service-oriented architecture that lies at the heart of modern cyberinfrastructure implementations and, especially, grids. The most widely used implementation is based on web services. Web services are an extension of the widely used world wide web, which implements direct, automated peer-to-peer (i.e., computer-to-computer) communication. Web services provide standard mechanisms for the publishing, discovery, execution, and management of distributed component services, which include everything from instruments to data archives in the context of ocean observatories. As discussed in Section 3.6, many aspects of an ocean observatory service-oriented architecture may be adapted from related cyberinfrastructure projects, although some components (notably the infrastructure services required to manage the internal parts of an ocean observatory) will be new.

In addition to the service-oriented architecture, successful implementation of ocean observatories will require the seamless integration of modern visualization technologies at many levels. Many high-quality research products exist in this area that can be adapted as an essential element of an ocean observatory cyberinfrastructure.

Designing Ocean Observatories

Sound system engineering practices must be used from the initiation of the ocean observatory design cycle. In particular, the design of ocean observatories must be driven by the needs of the scientific community who will use the facilities. Extracting requirements from the scientific community presents a challenge to the engineering team responsible for ocean observatory design, as the typical science user cannot readily quantify present and

future needs that will lead to a formal design, and may not be familiar with the relevant power, communications, control, and ocean engineering technologies.

To solve this dilemma, the engineering team has to construct a wide range of use scenarios incorporating representative suites of sensors and platforms in close collaboration with a broad group of potential science users, and extract from these a set of initial requirements for an ocean observatory system. The initial requirements are used to define an initial system architecture that is compared to additional use scenarios. The result is an iterative design process carried out by an interactive team of scientists and engineers, which comprises a major component of a formal system engineering process.

The entire design process must be guided by a set of overarching principles that comprise the top-level science requirements. These principles can be specified *a priori* rather than being extracted from use scenarios, as they represent the overall ocean observatory design philosophy. Further, this list should be as short as possible, both to simplify the design cycle and to avoid potential conflicts.

The following is an example set of generic top-level design requirements. Not all of these need apply to a given installation; for example, several are specific to multi-node observatories, and may be irrelevant for single-node implementations. The ordering does not imply priority.

- **Lifetime:** An ocean observatory shall meet all science requirements, with appropriate maintenance, for a design life of at least 25 years.
- **Cost:** An ocean observatory shall be designed to minimize the 25 year life cycle cost.
- **Reconfigurability:** An ocean observatory shall allow resources to be dynamically directed where science needs and priorities dictate.

- **Scalability:** An ocean observatory shall be expandable, so that additional science nodes that meet observatory reliability goals can be placed near or at locations of interest that may develop in the future.
- **Upgradeability:** An ocean observatory shall be upgradeable to accommodate future technology improvements.
- **Robustness:** An ocean observatory shall utilize fault tolerant design principles and minimize potential single points of failure.
- **Reliability:** The primary measure of ocean observatory reliability shall be the probability of being able to send data and commands between any science instrument and shore or another science node, exclusive of instrument functionality.
- **Futurecasting:** An ocean observatory shall have functionality and performance significantly beyond that required to support current use scenarios so that experiments and instruments that may reasonably be anticipated to develop over the expected life of the facility can be accommodated.
- **Open Design Principle:** Ocean observatory hardware designs and specifications shall be freely and openly available, and all software elements shall be based on open standards to the greatest extent possible.

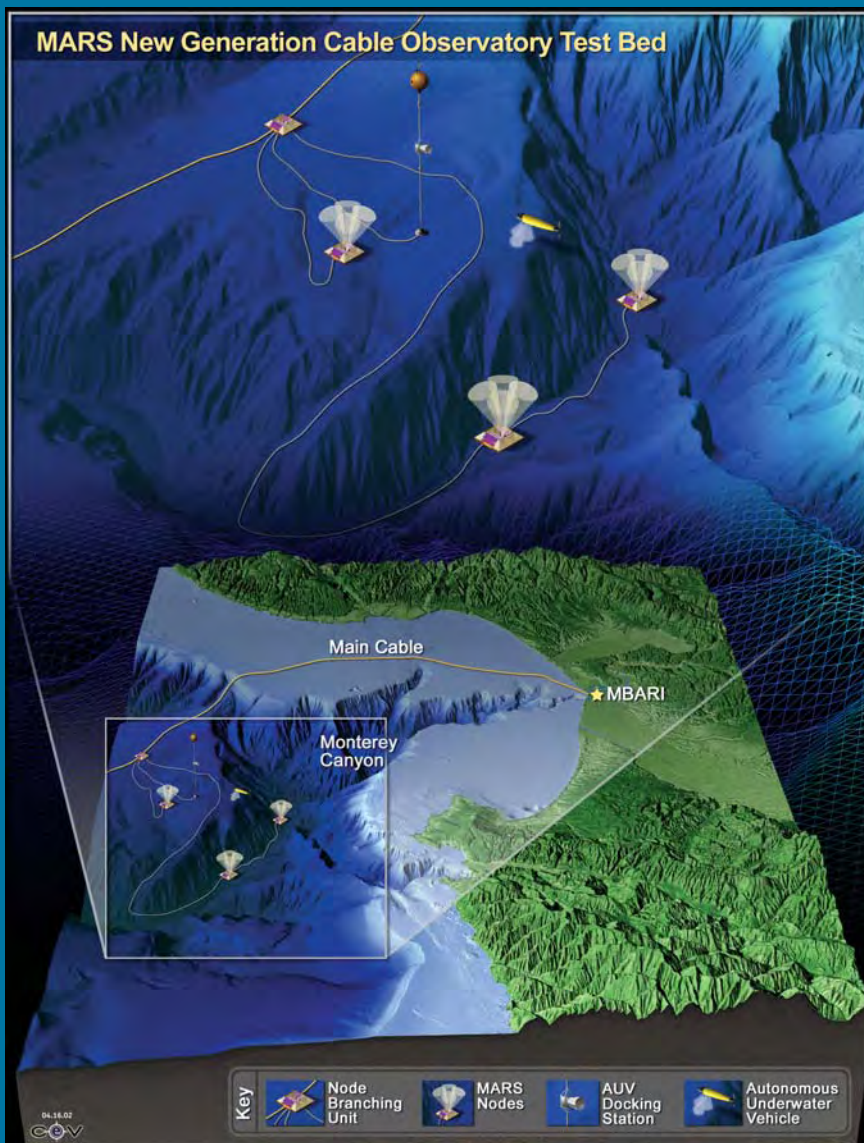
A major challenge in ocean observatory design lies in reliability engineering. The electronic infrastructure required to implement an ocean observatory will always be complex, and constructing an installation that delivers the required performance and is maintainable at a reasonable cost is critical to their success. High-reliability engineering is a critical element in minimizing the life cycle cost (defined as the sum of capital costs plus total operating costs over the lifetime of the system) of ocean observatories. Thorough life cycle cost estimates and projecting operations and maintenance (O&M) costs are an essential ocean observatory design element.

SIDEBAR 4.0. THE MONTEREY ACCELERATED RESEARCH SYSTEM (MARS)

A major concern in the engineering of large, complex projects that contain significant new applications of technology is minimizing the risk of major problems or even failure. One useful approach to risk mitigation is the construction of a scaled-down version (or testbed) that still contains most of the critical elements of the full system. Engineering of the infrastructure for the most complex element of the OOI, the regional cabled observatory (RCO), has been ongoing for over three years. The Monterey Accelerated Research System (MARS) will be installed off Monterey, California, as a testbed for the RCO in late 2005.

MARS consists of a single undersea node containing prototypes of the power, data communications, time distribution, and observatory management subsystems for the RCO that have been designed and which will be incorporated in the multi-node system. The MARS node (see Figure 4.3) will be installed by a commercial cable vessel in about 900 m of water at the end of ~70 km of buried submarine fiber optic cable. In the initial year or two of operation, thorough testing of the RCO system design will enable early detection of unforeseen design problems. Further, rapid access to the MARS node will allow economical modifications to be made, if necessary. Finally, on the longer term, MARS will serve as a testbed for the evolving ocean observatory cyberinfrastructure without placing more complex OOI elements at risk as a development system.

Throughout the life cycle of ocean observatories, the MARS system will also serve as an instrument development testbed. Because it is accessible on a day basis from the Monterey Bay Aquarium Research Institute, prototype instruments can be installed and removed quickly and economically, resulting in a substantial acceleration of the instrument development cycle. As a result, fully working instruments will be available for installation on the RCO (or other ocean observatories) more rapidly after their conception and design, maximizing the scientific return of the OOI.



Cartoon showing the Monterey Accelerated Research System (MARS), which consists of a single regional cabled observatory node at the end of ~70 km of submarine fiber optic cable in ~900 m of water.



CHAPTER 5. EDUCATION AND PUBLIC AWARENESS

“Education has provided the skilled and knowledgeable workforce that made America a world leader in technology, productivity, prosperity, and security. However, rampant illiteracy about science, mathematics, and the environment now threatens the future of America, its people, and the oceans on which we rely.”

Report of the U.S. Commission on Ocean Policy (2004)

The real-time data and high-speed communication capabilities of ocean observatories will open entirely new avenues for diverse student and public audiences to interact with and understand the Earth and oceans. Through an expanding array of learning environments (Figure 5.1), people of all ages will be able to participate in our journey of scientific exploration and discovery. The same OOI technology that promises to change fundamentally how ocean science research is conducted also has the potential to invigorate science education in the United States.

A 2003 report from the National Science Board (NSB) states “Science and technology have been and will continue to be engines of U.S. economic growth and national security. Excellence in discovery and innovation in science and engineering (S&E) derive from an ample and well-educated workforce” (NSB, 2003). And yet, as observed in another NSB report, “...a troubling decline in the number of U.S. citizens who are training to become scientists and engineers, whereas the number of jobs requiring science and engineering (S&E) training continues to grow,” and that these trends “threaten the economic welfare and security of our country” (NSB, 2004).

If the OOI’s innovative, *in situ* observatory network is to become a constant source of technological innovation and scientific discovery, there must be a workforce positioned to ensure high returns on this research investment. This workforce includes scientists, engineers, and

operational oceanographic technicians with very different skill sets than are currently being taught. Key to achieving this goal are: (1) fostering a well-informed citizenry that appreciates the complexities of the Earth system and its role in their lives, the ocean’s role in this system, and the benefits of scientific research in their lives; (2) encouraging all students from grade school through college to consider careers in science, technology, engineering, and mathematics; and (3) providing appropriate learning environments in which students and professionals develop the scientific and technical skills required to succeed in diverse science and technology careers.

Scientists and Educators Working Together

To meet these challenges, ocean scientists and educators are working together to ensure that educational needs are factored into observatory planning from the beginning. At the ORION community workshop held in San Juan, Puerto Rico in January 2004, approximately 40 of the 300 attendees were science educators. This approach broke new ground, as education programs were viewed as a cross-cutting theme from the outset and educators of various specialties participated in the scientific working groups. An IOOS education report is also now available (Ocean.US, 2004) and close coordination between IOOS and ORION in the development of observatory-based education initiatives will be critical.



Figure 5.1. The real-time data and high-speed communications inherent in ocean observatories will open new avenues for citizens of all ages to learn about the oceans and to participate in the excitement of scientific discovery and exploration. Image provided courtesy of the NEPTUNE Project (www.neptune.washington.edu) and the Center for Environmental Visualization.

Decisions are pending regarding OOI funding for infrastructure related to education vs. ORION funding for educational programs. The Education and Public Awareness Committee being formed as a subcommittee of the ORION Executive Steering Committee is expected to provide advice and guidance to NSF on this matter. This committee will also assist and guide the preparation of the education and public awareness national strategy and implementation plan for the OOI and ORION, including close coordination with the IOOS education efforts.

Building Educational Capacity

Education programs that capitalize on the OOI's observatory infrastructure have the potential to impact profoundly the nation's overall capacity in science and technology education thereby enlarging and diversifying the cohort of pre-college and university students motivated to pursue science and technology studies. To reach these students, opportunities that raise awareness of observatories must be provided to educators at all stages in their

career development, from their initial undergraduate education through graduate studies, to their long-term professional development.

Educators enthused and inspired by ocean science research will in turn stimulate and motivate more students to pursue course work in science and technology and to perform at levels necessary to excel in related careers. Informal educators in science centers and museums who are trained and empowered to support the ocean observatory effort will also be ready to inform and excite the public at large—adults, family groups, youth, and senior citizens. Educational programs designed for the OOI infrastructure will be ground-breaking in the way they fully embrace and integrate the huge volume of real-time and near-real-time data and imagery, the diverse types of data and information products, and an ever-growing reservoir of archived data.

Potential foci for informal education associated with the OOI include museum and science center exhibits, IMAX movies, youth group projects (e.g., Girl Scout, 4-H, Boys and Girls Clubs), television documentaries, and volunteer programs. Curiosity-driven ocean-education web sites such as “Dive and Discover” (<http://www.divediscover.whoi.edu/>) and real-time ROADNet (<http://roadnet.ucsd.edu>) have had tremendous popularity, as have articles in the popular press. Video streamed over the web from undersea research projects can be spectacular, spotlighting newly discovered life forms, or hydrothermal vents and deep ocean canyons. Scientific visualizations enable users to “see into” and experience the oceans in ways not previously possible. In other cases, observatories will help provide basic, useful information for boaters, surfers, or fishing enthusiasts as they plan their days. Each time an observatory discovery reaches the public, people will learn more about the ocean and how it works.

Using ocean science as a vehicle for formal education has garnered attention through current activities (e.g., Rutgers’ COOL Classroom <http://www.coolclassroom.org/home.html> [see Sidebar 5.0] and MBARI’s EARTH Program <http://www.mbari.org/education/earth/>), and

for its broader potential in developing scientific literacy. Observatory science is particularly well suited to help students and educators understand the difficult and sometimes neglected unifying concepts and processes of science and the science-as-inquiry content of the National Science Education Standards.

ORION Workshop Recommendations

The January 2004 ORION workshop report outlines a number of broadly defined goals for next-generation geosciences education associated with ocean observatories. The first three goals, listed below, form the basis of what the ORION could contribute to a national ocean observing education infrastructure and may be regarded as constituting the core goals of the ORION education and public awareness plan.

Form an education and communications coordination office. The primary purpose of the Education and Communications Coordination Office is to ensure that the OOI/ORION education and communications efforts are sufficiently coordinated, coherent, and sustained so the education and communication goals are achieved. Chief among the priorities of this office will be to coordinate with other Earth and ocean science education organizations. (See Table 1.)

Establish a data management and content translation facility. A task force of educators, researchers, and technical specialists will investigate the efficacy of various methods for bringing observatory data to the public, students, and educators. The focus will be on facilitating the creation of learning resources for exhibits, multimedia, community programs, and curricula development that use real-time and near real-time data streams, imagery and visualizations. The task will require close coordination among science educators, science visualization experts, technical experts, and science content experts, among others. The Digital Library for Earth System Education has committed to being a partner in this effort.

SIDEBAR 5.0. COOL CLASSROOM AND EARTH

Ocean observatories offer the potential to help a broad range of user groups understand how the ocean varies over time and space. Events such as the passing of Hurricane Floyd over the cabled Long-term Ecosystem Observatory (LEO) in 1998, and recent studies of the buoyant river plume of the Hudson River have provided opportunities for educators and scientists to develop and test applications of the data for a variety of user groups including K-12 students, teachers, recreational boaters, fishermen, and tourists along the New Jersey shore.

COOL Classroom (The Coastal Ocean Observation Laboratory Classroom sponsored by Rutgers-IMCS) and EARTH (Education and Research: Testing Hypotheses program sponsored by the Monterey Bay Aquarium Research Institute) have created the first of what will be a series of educational products and services

for the K-12 community that capitalize on ocean observing data. EARTH and COOL Classroom are Internet-based instructional modules that link students with research investigations at observing systems. EARTH lays new groundwork, providing teachers with means for integrating real-time data with existing educational standards and tested curricula in an interactive and engaging way. The COOL Classroom consists of classroom projects designed to teach science concepts such as vector addition using with CODAR data, and food web dynamics and ocean weather forecasting with sea surface temperature, ocean color, and weather data. Although developed with limited funds, EARTH and COOL Classroom provide the raw materials from which new educational products can be developed through collaborations between the observing system and formal education community.

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Rutger's COOL Classroom web portal.

TABLE 1. OOI EDUCATION COLLABORATORS

- **National Marine Educators Association (NMEA), Centers for Ocean Science Education Excellence (COSEE):** ocean science literacy standards
- **American Geophysical Union (AGU), American Society for Limnology and Oceanography (ASLO), Earth System Science Education in the 21st Century (ESSE-21), IOOS:** diversity initiatives in the ocean science workforce
- **Global Learning and Observations to Benefit the Environment (GLOBE), American Meteorological Society (AMS), Research and Education: Volcanoes, Exploration and Life (REVEL), Geography Alliances, Sea Grant, NOAA's Office of Exploration:** educator preparation and development of leaders who train other educators to use ocean observatory information in curricula, exhibits, and programs
- **IOOS, Sea Grant, COSEE, GLOBE, AMS:** participation by these groups in local science education improvement initiatives
- **Marine Advanced Technology Education (MATE), RIDGE2000:** Education for student science and technology competitions
- **Digital Library for Earth System Education (DLESE):** education cyber-infrastructure, including community services and digital library for learning materials
- **NASA, COSEE:** story development and supporting visuals.

Establish a community of educator leaders who coordinate, sustain, and support local education leadership in their science education improvement initiatives. The correlation between educator preparedness and student/adult participation in and support of science is strong; thus, investing in professional development programs is an investment in the future scientific workforce and a science-supportive society. Future educators, at all levels, including undergraduate, graduate, and informal must be provided with the tools to construct meaningful and coherent curricula and learning materials from the vast array of online learning resources that will be available from the OOI and ORION.

Coordination with Other Programs

Capitalizing on existing networks and programs and their participation in the larger Earth/geography/space system collaborative is vital. Because the education sys-

tem in the United States is large, complex, and driven by local issues, and because learning is a life-long process, it is very difficult for any group of educators acting alone to effect measurable improvements in education when the challenges transcend disciplines, departments, agencies, and institutions. Building a collaborative education network from existing networks is one way that individual groups can have a positive impact far beyond that possible when acting alone.

Some of the most prominent collaborations will be with organizations listed in Table 1. IOOS is a particularly strong partner because of the overlap in goals and technologies. Major recommendations coming out of a recent IOOS education workshop are very similar to the ORION San Juan workshop recommendations. The broad community consensus in these three areas argues strongly for a closely coordinated, perhaps even common

education effort between these two programs. Both the ORION and IOOS detailed education implementation plans will address how that is to be achieved.

Described in this chapter are plans and goals for implementing powerful OOI and ORION education and public awareness programs in which technology will play a major role whether the approaches are traditional or transformational. However, planners of educational programs for the OOI and for ORION must remain aware of the continuing need for fundamental rather than only incremental reforms in U.S. formal science education, even as the nation is in the midst of fundamental, if slow, reform.

As Phillip Bond, Department of Commerce Undersecretary for Technology, stated at the Enhancing Education Through Technology Symposium in Pasadena, California in April 2004, "Rather than using technology to imitate or supplement conventional classroom-based approaches, exploiting the full potential of next-generation technologies is likely to require fundamental, rather than incremental reform...Content, teaching, assessment, student-teacher relationships and even the concept of an education and training institution may all need to be rethought...we cannot afford to leave education and training behind in the technology revolution. But unless something changes, the gap between technology's potential and its use in education and training will only grow as technological change accelerates in the years ahead."

Communicating the great educational potential of ocean observatories and the need for changes and collaborations at all levels of the educational process in the United States, should be important components of OOI education and public awareness planning.



CHAPTER 6. LINKS AND PARTNERSHIPS

The research-driven ORION/OOI is part of a broader national and international effort to establish long-term observatories in the ocean, both for conducting basic research and for operational oceanographic needs. The scientific planning, management, and organizational structure of the ORION/OOI Program will be configured to maximize the synergies with these other efforts. Ocean observatories also offer unique opportunities for academic-government-industry partnerships in the construction, installation, and operation of ocean observatory infrastructure.

Partnerships with Operational Ocean Observing Programs

The last decade has seen the development of a number of national and international programs designed to observe the ocean and provide timely, useful, and practical information to a variety of users in areas such as fisheries management, maritime shipping and safety, public health, homeland security, tsunami warning, and weather and climate forecasting. In the United States, this operational observing system is known as the Integrated Ocean Observing System (IOOS). The IOOS is being developed as a contribution to the international Global Ocean Observing System (GOOS) (<http://ioc.unesco.org/goos/>). GOOS is a system for observations, modeling, and analysis of marine systems designed to provide accurate information products about the state of the global ocean and its living resources, as well as forecasts of future ocean conditions.

On a broader scale, the international Global Earth Observation System of Systems (GEOSS) (<http://www.epa.gov/geoss/index.html>) is dedicated to the development of a comprehensive, coordinated, and sustained Earth

Observation System to collect and disseminate improved data and models to stakeholders and decision-makers. In April 2004, the United States along with more than 50 nations formally adopted a ten-year implementation plan for a Global Earth Observation System. The emerging system will focus on nine areas for societal benefit:

- Improve weather forecasting
- Reduce loss of life and property from disasters
- Protect and monitor our ocean resource
- Understand, assess, predict, mitigate, and adapt to climate variability and change
- Support sustainable agriculture and forestry, and combat land degradation
- Understand the effect of environmental factors on human health and well-being
- Develop the capacity to make ecological forecasts
- Protect and monitor water resources
- Monitor and manage energy resources

While GEOSS transcends the ocean sciences, GOOS will represent the ocean contribution to this effort. An international, nongovernmental, project related to GOOS is OceanSites (<http://www.oceansites.org/OceanSITES/>). OceanSites has prioritized fixed-point time-series sites to complement other observing system components including satellites, moorings, and ships. These Eulerian observatories are uniquely suited for sampling two of the four dimensions (depth and time) and so will provide multidisciplinary resolution of variability in processes like biological productivity and the oceanic-atmospheric fluxes of carbon dioxide, heat, freshwater, or momentum. Further, OceanSites will provide opportunities for seismic and related geophysical observations to improve understanding of Earth structure and tectonics. The International Ocean Network

(ION) (<http://www.deos.org/ion/>) is another nongovernmental organization formed to facilitate international collaboration in the development of seafloor observatories, primarily for Earth science studies.

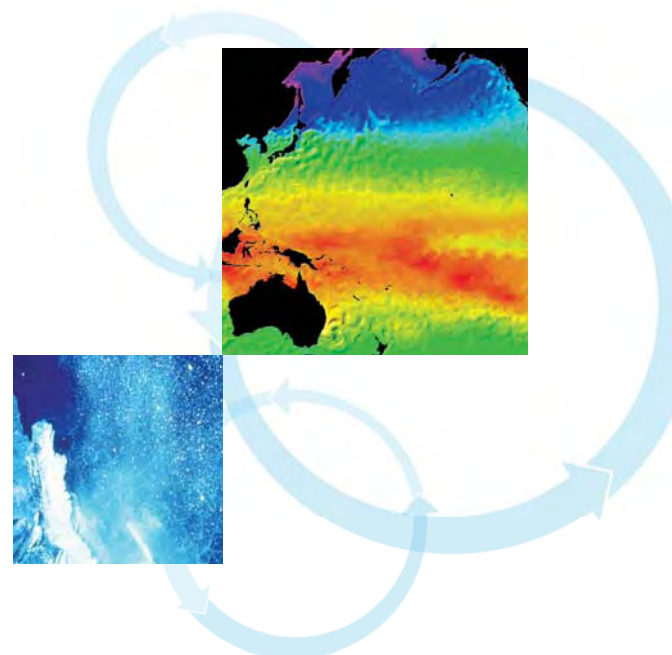
At the national level, ORION/OOI's closest links will be to the IOOS. The two programs are different in terms of motivation: IOOS is focused on providing sustained, timely, and improved information products to decision-makers to address seven societal needs currently limited by these factors, while ORION/OOI aims to develop new knowledge and technology to advance understanding of the oceans and its role in the Earth system. However, the two share many common interests and should be viewed as essential components of a unified effort to observe the oceanic realm. Advances in fundamental knowledge of ocean processes provided by ORION/OOI will be essential for IOOS to achieve its longer-term operational goals. ORION/OOI will also foster the development of new sensors and observatory technologies, including the capability to make continuous automated observations of biological and chemical processes in remote and extreme environments, which can eventually transition into the IOOS operational network. The flexibility to optimize spatial and temporal resolution provided by the OOI infrastructure will allow systematically better approaches to testing parameterizations of models that will, in turn, improve IOOS sampling schemes, models, and information products.

OOI/ORION research and education projects will develop professionals with expertise and skills in cutting-edge observing technologies, information management and visualization techniques that will be needed by both ORION and IOOS. At the same time, IOOS observations will provide ORION/OOI researchers with sup-

porting information that will permit these investigations to be placed into a broader spatial and temporal context. IOOS will also provide scientists using research observatories with results from operational physical and biogeochemical models to help design sampling regimes and interpret results. And IOOS operations, systems integration and education efforts will develop the skilled operational oceanographic professionals that both OOI/ORION and IOOS will need to sustain the in-water infrastructure. While independent efforts, the ORION/OOI and IOOS programs are more than complementary but rather strengthen each other; these two programs will need to be closely coordinated at all stages, from conception and planning through installation and operation.

Partnerships with Other Research-Driven Ocean Observatory Programs

Planning for ocean observatories is advancing in many nations, much of it done in close collaboration with efforts in the United States. The OOI's closest international partner is NEPTUNE Canada (<http://www.neptune->



canada.ca/), which will build a cabled observatory offshore of Vancouver Island (see Sidebar 6.0). NEPTUNE, a proposal to build a regional, plate-scale cabled observatory in the Northeast Pacific Ocean, involves a consortium of institutions, including the University of Washington, the University of Victoria (Canada), Woods Hole Oceanographic Institution, the Monterey Bay Aquarium Research Institute, and the Jet Propulsion Laboratory (<http://www.neptune.washington.edu/>). NEPTUNE Canada has received funding from the Canadian Foundation for Innovation and from the British Columbia Knowledge Development Fund and is now soliciting contractors to carry out the deployment of the northern portion of the proposed NEPTUNE observatory. A formal Memorandum of Understanding for coordination has been signed between the University of Victoria and the National Science Foundation, and an operating collaboration has been negotiated between NEPTUNE Canada and the ORION/OOI Project Office.

Japan currently operates the largest existing network of seafloor observatories: eight cabled observatories in place around the Japanese islands, mostly for earthquake monitoring and research. In 1996, the Ministry of Education, Science, Sports, and Culture in Japan funded the Ocean Hemisphere Project (OHP) to establish a network of multidisciplinary ocean observatories in the Pacific Basin. The OHP network includes island stations and seafloor observatories making seismic, electromagnetic, and geodetic measurements, including three broadband seismometers installed in ODP drillholes in the western Pacific. Japanese scientists are currently planning a next-generation submarine cable network known as ARENA that aims to provide a network of cabled observatories spanning the plate boundary along the Japan Trench. As with the OOI, it is anticipated that the observatories will be multidisciplinary, allowing researchers to collect a variety of seismic, oceanographic, and biological information. ARENA is expected to have a mesh network topology and power and communication requirements that are very similar to the OOI regional cabled observa-

tory. There will thus be many opportunities for potential collaboration, both technically and scientifically, as these projects move forward.

The ESONET consortium (<http://www.abdn.ac.uk/ecosystem/esonet/>) is a major research-driven ocean observatory program developing in Europe. ESONET proposes to install a network of long-term, cabled seafloor observatories at key provinces around the European margin. These observatories will be located beyond the continental shelf edge in water depths up to about 4000 m and will support multidisciplinary research in geophysics, tectonics, chemistry, biochemistry, physical oceanography, biology, and fisheries. ESONET will not be a single integrated network, but a federation of local networks covering different geographic regions. Though still in the planning stages, there are numerous opportunities for future collaboration between ESONET and the OOI.

Links to Other Earth/Environmental Observatory Programs

Distributed sensor networks and observing systems are being developed to address a broad range of Earth system questions and environmental problems. Although many of these efforts are not specifically oceanographic, the connections can be very strong nonetheless. For example, EarthScope's Plate Boundary Observatory (PBO) is a geodetic observatory designed to study the three-dimensional strain field resulting from deformation across the active boundary zone between the Pacific and North American plates in the western United States. It will consist of arrays of GPS receivers and strainmeters that will be used to deduce the strain field on time scales of days to decades as well as geologic and paleoseismic investigations to examine the strain field over longer time scales. The USArray component of EarthScope is a continental-scale seismic observatory designed to provide a foundation for integrated studies of continental lithosphere and deep Earth structure over a wide range of scales. However, both PBO and USArray are confined

SIDEBAR 6.0. NEPTUNE CANADA

The OOI's closest international partner is NEPTUNE Canada (<http://www.neptunecanada.ca/>). NEPTUNE, a joint project involving the University of Washington, Woods Hole Oceanographic Institution, Monterey Bay Aquarium Research Institution, Jet Propulsion Laboratory, and the University of Victoria (Canada), is a proposal for a 3,000 km network of powered fiber optic cable with about 30 instrumented nodes spaced about 100 km apart located on the seabed over the Juan de Fuca tectonic plate, a 200,000 sq km region in the northeast Pacific off the coasts of British Columbia, Washington and Oregon (<http://www.neptune.washington.edu/>). Scientific and engineering planning, which has been ongoing for more than a decade, has been fully integrated between the two countries.

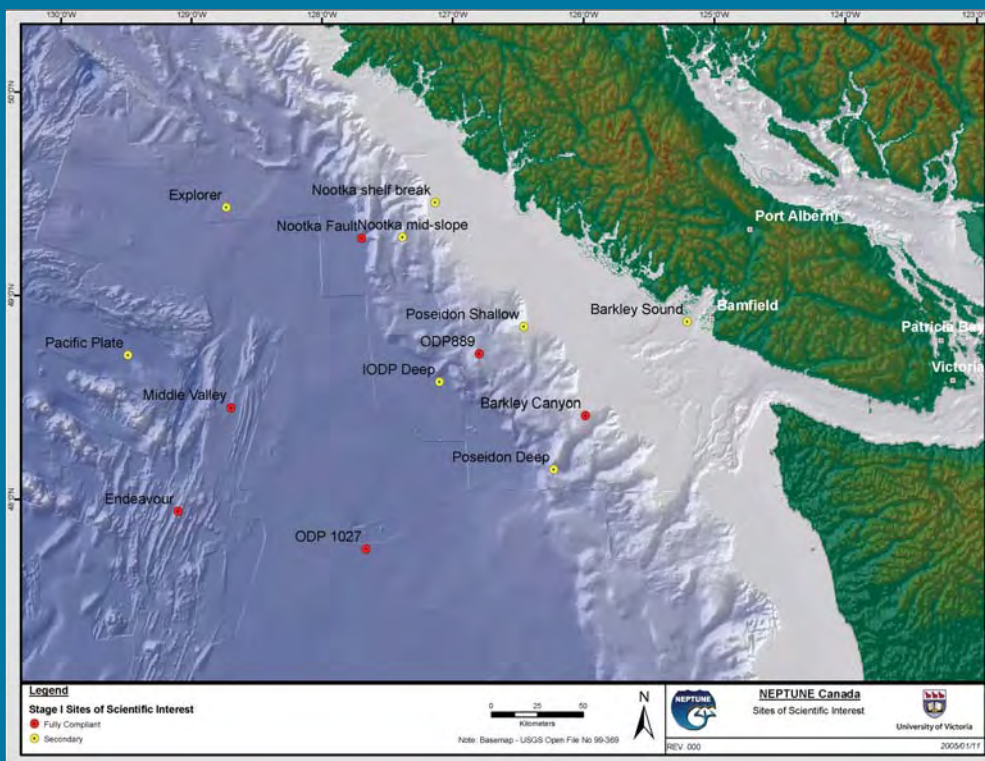
Some of the major scientific topics to be addressed by the NEPTUNE project include:

- Plate tectonic processes and earthquake dynamics;
- Deep-sea ecosystem dynamics;

- Dynamic processes of fluids in ridge environments;
- Dynamic processes of fluids and gas hydrates on the continental margin;
- Engineering and computational research; and
- Ocean and climate dynamics and effects on marine biota.

The University of Victoria has received funding from the Canadian Foundation for Innovation and from the British Columbia Knowledge Development Fund to install VENUS (Victoria Experimental Network Under the Sea), a coastal observatory off the southern British Columbia coast, and the northern portion of the NEPTUNE observatory offshore Vancouver Island. The process of soliciting contractors to carry out the installation of the Canadian-funded portion of NEPTUNE is currently underway and this part of the system is expected to be operational in 2008. NEPTUNE Canada is thus starting about two years ahead of the OOI, and their experience on many levels will prove a valuable asset to the U.S effort. A formal Memorandum of Understanding

for coordination has been signed between the University of Victoria and the National Science Foundation, and an operating collaboration has been negotiated between NEPTUNE Canada and the OOI Program Office.



Map showing the location of planned NEPTUNE Canada cabled observatory off Vancouver Island. Red circles show location of planned observatory nodes.

to onshore sites. Seismic and geodetic measurements in offshore coastal regions, like those that will be enabled by a regional-scale cabled observatory in the Northeast Pacific, will provide a critical offshore complement to EarthScope's PBO and USArray.

Some projects, such as the hydrologically oriented CLEANER and CUASHI, will ultimately generate important riverine forcing data sets for OOI coastal observatories. NEON will provide detailed information on the biosphere that may prove particularly useful in connection with ocean observatory biogeochemical research. Discussions are already underway among these different programs to reach agreement on metadata and data standards, and data management approaches, to ensure that these systems provide easily accessible, consistent information to all users.

Links with Ocean Science Research Programs

A wide range of process-oriented research programs recognize the importance of capable, sustained measurements in the ocean and are expected to forge partnerships with the ORION/OOI. Within the ocean biogeochemical and biological research communities, the Joint Global Ocean Flux Study (JGOFS) has provided a tangible example of the benefits of sustained observations. Initially, measurements at the JGOFS time-series study sites (HOT and BATS) were limited to a small suite of relatively simple measurements that could be performed routinely to examine temporal variability. As JGOFS evolved, however, the power of sustained observations and the ability to place measurements into a known temporal context became apparent. Measurements were added and other, separately funded, research programs collocated at these sites. Consequently, as JGOFS progressed, greater numbers of research projects were attracted to these locations by the very nature of time-series studies: an extensive, multi-year data framework in which to test novel concepts and validate emerging models. New paradigms have been conceived and brought to fruition at the time-series sites.

Building on this success, establishing additional time-series research sites is a high priority for future marine biogeochemical and ecological research. For example, the science plans of both the Integration of Marine Biogeochemical and Ecological Research (IMBER) and Ocean Carbon and Climate Change (OCCC) Programs specifically propose process studies at additional coastal and open ocean time-series sites. Similarly, the GEO-TRACES Program Science Plan outlines studies of exchange of trace elements and isotopes at time-series sites at air-sea, benthic, and continental margin interfaces and proposes that large hydrographic measurement surveys be anchored at time-series sampling locations. ORION activities, and specifically OOI infrastructure, could provide the basis for these distributed time-series study sites.

Research activities focused on the seafloor also call for expanding sustained-observation technologies. The IODP is already establishing borehole seismic and crustal fluid observatories with planned continuous observations provided by *in situ* instruments (see Sidebar 3.5). Episodic processes and transport controlled by specific thresholds are widely recognized to control the geomorphology, dynamics, and sediment distributions of continental margin systems. As such, the MARGINS program has numerous activities that require sustained observations capable of capturing specific events. Examples include the study of sediment transport within the Source to Sink (S2S) initiative and earthquakes within the Seismogenic Zone Experiment (SEIZE) and Subduction Factory (Sub-Fac) initiatives. The RIDGE2000 (R2K) program also requires sustained observations for "time-critical studies" of episodic magmatic and tectonic events, and associated hydrothermal and biological response to these events. The OOI infrastructure can provide an interactive, real-time observing presence at the R2K program's three Integrated Study Sites.

At the sea surface, the OOI infrastructure can provide continuous measurements of specific, remotely sensed parameters to provide unprecedented ground-truthing

of remotely sensed variables. Combining such measurements with other sensed quantities may facilitate the development of new products and parameters based on a hybrid of remotely and *in situ*-sensed information fueling new Earth science satellite-based missions.

Given the growing interdisciplinary nature of oceanographic research and the fully integrated data streams anticipated through ORION/OOI observatories, it is anticipated that the central role of observatories in basic oceanographic research will expand to encompass all marine subdisciplines.

Partnerships with Industry

The design, construction, installation, and operation of ocean observatories will provide numerous opportunities for academic-government-industry collaboration. The energy and telecommunications industries have a great deal of relevant expertise that will be useful in the design of OOI infrastructure (see Chapter 5). For example, the submarine telecommunications industry builds extremely reliable wet hardware to facilitate high-bandwidth data transport in submarine cables. The energy industry has extensive experience with the construction and operation of large moored platforms and, increasingly, in the use of autonomous subsurface platforms. Because the academic community does not have the capacity to manufacture many observatory components (e.g., large spar buoys, fiber optic cable, many types of sensors), industry will be contracted to supply much of this equipment. Industry may also play an important role in providing the support services (ships, ROV) needed to install, maintain, and operate these systems. Strengthening ties between the academic science community and industry for the development of ocean observatory infrastructure will accelerate the application of increasingly sophisticated technological solutions to ocean science problems. This outcome will broadly benefit the field of oceanography.

CHAPTER 7. PROGRAM MANAGEMENT AND IMPLEMENTATION



A project as large and complex as the OOI requires an extensive planning and program management effort prior to the installation of the first observatory infrastructure. The management of the OOI will be guided by the requirements of NSF's Large Facilities Management and Oversight Guide (<http://www.nsf.gov/pubsys/ods/getpub.cfm?nsf03049>) and the management principles recommended by the National Research Council Report *Enabling Ocean Research in the 21st Century* (<http://www.nap.edu/catalog/10775.html>).

The presentation of a detailed program management and implementation plan, including the types of assets that will be acquired and their location, is beyond the scope of this document, and will be developed by the ORION Program Office in conjunction with the preparation of a formal OOI Project Execution Plan (PEP). In this chapter we briefly outline some of the major steps in the development and implementation of the PEP.

ORION Program Office

An essential first step, and an important milestone in the development of the OOI and the ORION Program, was the establishment of an ORION Program Office in early 2004. The Program Office (<http://www.orionprogram.org/>) will include, when fully staffed, a director, program manager, systems engineer, cyberinfrastructure specialist, education and outreach coordinator, and a small support staff. It is responsible for coordinating the scientific planning, program element engineering, cyberinfrastructure development, and education and

outreach efforts for the ORION Program and OOI. An ORION Executive Steering Committee (ESC) was also established in early 2004 to provide scientific and technical advice to the Program Office. As planning progresses, appropriate standing and *ad hoc* committees are being established by the ESC to provide advice from the broader scientific and engineering communities on the development of the OOI and the ORION Program. The membership of these committees will come from academia, industry, government, and the international community, and will include scientists, engineers, and educators with broad, interdisciplinary expertise in ocean-related problems.

Although the ORION Office will be responsible for overall program management, the actual construction, installation, and operation of the observatories that comprise the OOI will be subcontracted by the Program Office to consortia, individual institutions, or companies, each of whom will require a formal but semi-autonomous project-management structure. This decentralized management style will promote maximum creativity and the tailoring of each observatory system to the specific scientific goals and operational requirements of that particular system. Each operating entity will have flexibility of implementation (to encourage innovation), but will have to meet certain performance criteria in such areas as user interfaces, operations/maintenance, data management and archiving, and collaborations with the education and public awareness community as established by the ORION Program Office in consultation with the advisory structure.

Concept and Development Stage

Some key tasks for the ORION Program Office prior to funding of the OOI include:

- complete an OOI Science Plan (this document) that has been thoroughly vetted by the ocean science community
- solicit community input through peer-reviewed conceptual proposals for the use of OOI assets in order to refine the design of the ocean observatory infrastructure (including the types of assets that will be acquired and where they will be located)
- complete a thoroughly reviewed Project Execution Plan that describes the project organization and management; provides a work breakdown structure with final cost, schedule, and performance requirements; addresses safety, environmental, and health issues; explains plans for system integration, commissioning, testing, and acceptance; and describes oversight mechanisms and fiscal controls to ensure that the implementation tasks are completed on time and within budget
- facilitate integration of various OOI operating components, as appropriate
- facilitate the development and implementation of standards (e.g., for user power, communications, and time distribution interfaces, metadata requirements, system and subsystem reliability, and information management and archiving)
- coordinate scientific, engineering, and educational/outreach planning with other ocean observing programs, including IOOS and NEPTUNE Canada

Construction and Installation Stage

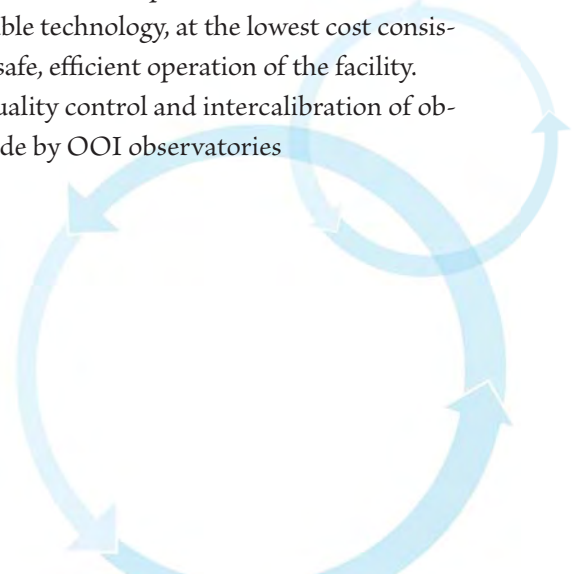
As OOI moves into the construction and installation phase of the program, responsibilities of the Program Office will broaden to include:

- producing an annual program plan and budget, and projecting these into the future
- selecting, through a competitive bidding process, contractors (either academic or industrial, as appropriate) for the construction and installation of observatory systems
- providing oversight of contracts
- managing liability issues
- selecting observatory operators and put in place appropriate oversight and review procedures
- ensuring that the scientific and technical components of international collaborations are coordinated effectively

Operations and Maintenance Stage

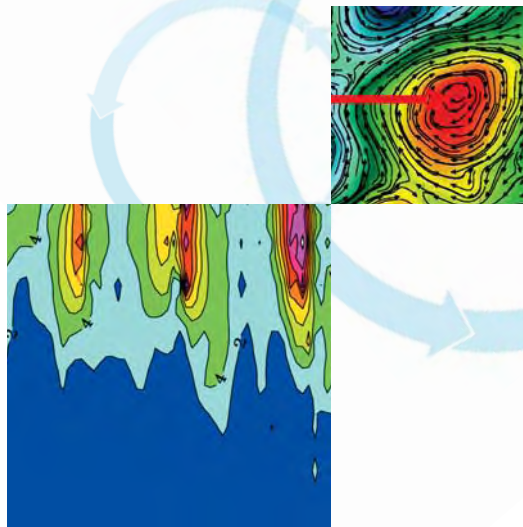
As observatories become operational, in addition to the above, the ORION Program Office must:

- ensure that access to observatories is dealt with fairly and consistently
- ensure that the observatory infrastructure supports the highest quality science and provides researchers with the best available technology, at the lowest cost consistent with the safe, efficient operation of the facility.
- ensure data quality control and intercalibration of observations made by OOI observatories



CONCLUDING REMARKS

The OOI represents a significant departure from traditional approaches in oceanography and promise to both transform the manner in which research is conducted in the oceans, and expand our understanding of the role of the oceans in planetary processes. In particular, the OOI will provide the infrastructure to integrate observations across vast scales from the microscopic and even submicroscopic (e.g., future DNA arrays deployed at observatories and the measurement of ground motion to the nanometer level) to the ocean basin (e.g., for studies of ocean circulation, climate variability, and Earth structure). Data collected by ocean observatories will be fully open and available for use by researchers, educators, government, and industry. The paradigm shift in ocean research enabled by the OOI will open entirely new avenues of research and discovery in the oceans, foster the development and application of advanced new technology to ocean science problems, provide exciting new opportunities for conveying the importance of the oceans to students and the general public, and acquire critical information for decision-makers in developing ocean policy.



APPENDIX 1

References and Suggested Reading

Executive Summary and Chapter 1. Introduction

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APPENDIX 2

Ocean Observatory Workshops and Related Reports

National Academy of Science/NRC Reports

- Illuminating the Hidden Planet: The Future of Seafloor Observatory Science
NAS/NRC, 2000, <http://www.nap.edu/catalog/9920.html>
- Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories,
NAS/NRC, 2003, <http://www.nap.edu/catalog/10775.html>

Community Planning Workshops and Reports

- Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean
JOI, 1988
- Workshop on Scientific Uses of Undersea Cables (Report to NSF, NOAA, ONR, USGS)
JOI, 1990
- JOI/IRIS Ocean Seismic Network: U.S. Pilot Experiment Task Force Meeting
JOI, 1991
- BOREHOLE: A Plan to Advance Post-Drilling Sub-Seafloor Science
JOI, 1994
- Broadband Seismology in the Oceans: Towards a Five-Year Plan
JOI, 1995
- Report of a Workshop on Technical Approaches to Construction of a Seafloor Geomagnetic Observatory
NSF, 1995, Technical Report
- Multidisciplinary Observatories on the Deep Seafloor
IFREMER, 1995
- Ocean Hemisphere Network Project
JAMSTEC, 1996, <http://www.eri-ndc.eri-u-tokyo.ac.jp>
- Proceedings of International Workshop on Scientific Uses of Submarine Cables:
Marine Geophysical Research Using Undersea Cables, JAMSTEC, 1997
- DEOS Global Work Group Report: Moored Buoy Ocean Observatories
NSF, 1999
- U.S. Carbon Cycle Science Plan
NSF, 1999
- DEOS Moored Buoy Observatory Design Study
NSF, 2000, <http://www.carboncyclescience.gov/planning.html>
- Symposium on Seafloor Observatories: Challenges & Opportunities, Key Largo, FL - Jan. '00
NAS/NRC, 2000
- Ocean Carbon Transport, Exchanges and Transformation (OCTET)
NSF, 2000, <http://www.msrb.sunysb.edu/octet/>
- NEPTUNE: Real-time, Long-Term Ocean & Earth Studies at the Scale of a Tectonic Plate
NSF, 2000, <http://www.neptune.washington.edu/pub/documents/documents.html>
- Long-Term Observations in the Oceans: Current Status and Perspectives for the Future
Workshop Report: Ocean Hemisphere Network Project (OHP) International Ocean Network (ION), OHP/ION, 2001

- Observing the Oceans in the 21st Century: A Strategy for Global Ocean Observations
Global Ocean Data Assimilation Experiment (GODAE), 2001
- Surface Ocean Lower Atmosphere Study (SOLAS)
NOAA, 2001, <http://www.aoml.noaa.gov/ocd/solas/>
- Ecological Determinants of Oceanic Carbon Cycling (EDOCC)
NSF, 2001, <http://picasso.oce.orst.edu/ORSOO/EDOCC/>
- Integrated and Sustained Ocean Observing System Workshop
Ocean.US, 2002, <http://www.ocean.us/documents/docs/FINAL-ImpPlan-NORLC.doc>
- An Integrated and Sustained Ocean Observing System (IOOS) For the United States: Design and Implementation
Ocean.US, 2002, <http://www.ocean.us.net/>
- Building Consensus: Toward An Integrated and Sustained Ocean Observing System -
OCEAN.US Workshop Proceedings, Virginia, March 2002, Ocean.US, 2002, Workshop
- Coastal Ocean Processes and Observatories: Advancing Coastal Research
NSF, 2002, <http://www.skio.peachnet.edu/research/coop/future.php>
- Office of Naval Research/Marine Technology Society Buoy Workshop
ONR, 2002, <http://www.whoi.edu/buoyworkshop/2004/index.html>
- Global Eulerian Observatories (GEO) International Science Team (HI)
2002
- Scientific Cabled Observatories for Time-Series (SCOTS)
NSF, 2003, http://www.geo-prose.com/projects/scots_rpt.html
- Implementation Plan for the DEOS Global Network of Moored-Buoy Observatories
CORE, 2003, <http://www.coreocean.org/deos/>
- Science Planning for the NEPTUNE Regional Cabled Observatory in the Northeast Pacific Ocean
(Report of the Pacific Northwest Workshop) NSF/NOPP/UW/OSU/PSU/N.Canada, 2003, http://www.neptune.washington.edu/pub/workshops/PNW_Workshop/ws_reports_documents.html
- Coastal Observatory Research Arrays: A Framework for Implementation Planning
(Report on the CoOP CORA Workshop, Nov. '03), NSF, 2003
- NEPTUNE Pacific Northwest Workshop
2003
- Biological and Chemical Instrumentation in the Ocean
WHOI, 2003, <http://www.whoi.edu/institutes/oli/activities/participants/jp3.html>
- DEOS Cable Re-Use Committee Report
NSF, 2003
- Science Use of Fiber-Optic Submarine Telecommunications Cable Systems
IRIS, 2003
- Ocean Observatories & Initiative Facilities Needs from UNOLS
UNOLS, 2003
- International Time Series Science Team: Report for POGO Meeting (Weller)
2003

- Autonomous and Lagrangian Platforms and Sensors (ALPS)
NSF, 2003, <http://www.geo-prose.com/ALPS/>
- Feasibility Study and Implementation Plan for the DEOS Global Network of Moored-Buoy Observatories
NSF, 2003
- Links between OOI and IODP Workshop
JOI, 2003, http://www.neptune.washington.edu/pub/documents/IODP_OOI_ReportSummary.pdf
- REgional Cabled Observatory Network (of Networks) (RECONN)
NSF, 2003, http://www.geo-prose.com/cabled_wksp/pdfs/reconn_rpt.3.2.04.pdf
- Technical Issues Related to Cable Re-use
2003, http://www.neptune.washington.edu/pub/documents/SubOptics2004_C_Abstracts2.pdf
- Coastal Observatory Research Arrays (CORA): A Framework for Implementation Planning
NSF, 2003, <http://www.ski.peachnet.edu/research/coop/cora.php>
- Ocean Research Interactive Observatory Networks (ORION) Workshop
NSF, 2004, http://www.geo-prose.com/projects/orion_report.html
- OCEAN.US Education Workshop
Ocean.US, 2004, <http://www.ocean.us/documents/workshop.jsp>
- Neptune CANADA Observing Systems
UVic, 2004, http://www.neptunecanada.ca/PDF/May2004NEPTUNE_Canada_OOS_Wkshp_Report_REVISED.pdf
- NSF Sensors & Instrumentation (MBARI)
NSF, 2004, http://www.mbari.org/rd/sensors/workshop_notes.htm
- Data Management and Communications Plan for Research and Operational Integrated Ocean Observing Systems
Ocean.US, 2004, http://dmac.ocean.us/dacsc/imp_plan.jsp
- RIver-dominated Ocean MARGins (RIOMAR)
2004, <http://www.tulane.edu/~riomar/>

Engineering & Technical

- Real-time, Long-term Ocean and Earth Studies at the Scale of a Tectonic Plate - NEPTUNE US Feasibility Study
2000, <http://www.neptune.washington.edu/pub/documents/documents.html>
- Feasibility of Canadian Participation in the NEPTUNE Undersea Observatory Network
2000, <http://www.neptune.washington.edu/pub/documents/documents.html>
- NEPTUNE: Desktop Study Volume1: Text
2002, <http://www.neptune.washington.edu/pub/documents/documents.html>
- NEPTUNE Data Communications System CoDR Final Report
2003, <http://www.neptune.washington.edu/pub/documents/documents.html>

Education & Outreach

- Technology, Science and Education: a Sea of Opportunities NEPTUNE Project
2001, <http://www.neptune.washington.edu/pub/documents/documents.html>
- NEPTUNE: The Teen Perspective
2001, <http://www.neptune.washington.edu/pub/documents/documents.html>
- NEPTUNE: Education and Outreach
2003, J Mar. Educ., 18
- The NEPTUNE Project
2003, JMar.Educ., 18
- REVELing in the SeaFloor
2003

APPENDIX 3

Time-Series Sites and Observatory Programs

Name	URL	Focus
North America		
AOOS	http://www.aos.org/	US - Alaska Ocean Observing System
ARGOS	http://noaasis.noaa.gov/ARGOS/	US-NOAA NESDIS - Data collection system for NPOESS satellite; met, oce
BATS	http://www.bbsr.edu/cintoo/bats/bats.html	BBSR - Bermuda Atlantic Time-series Study; mooring time series
BBMS	http://www.bonnebay.mun.ca/	Cn- Bonne Bay Marine Station Ocean Observatory;
C-GOOS	http://www.hpl.umces.edu/projects/wrkrpt.pdf	US - Coastal Global Ocean Observing System; workshop report
Canada Offshore-BuoyNetwork	http://www.atl.ec.gc.ca/msc/em/marine_buoys.html	Cn - Offshore Data Acquisition System, Maritime provinces; met, sea-state
Caro-COOPS	http://nautilus.baruch.sc.edu/carocoops_website/index.php	NC academics; Carolinas Coastal Ocean Observing and Prediction System
CeNCOOS	http://www.cencoos.org/	US - Central and Northern California Ocean Observing System
CBOS	http://www.whoi.edu/mvco/other_data/EC-COO/cbos.html	US - UMd; Chesapeake Bay Observing System
CMAN	http://www.ndbc.noaa.gov/	US-NOAA ; National Data Buoy Center
COMPS	http://comps.marine.usf.edu/	USFl; Coastal Ocean monitoring and Prediction System; West shelf Florida observatory.
CORMP	http://www.cormp.org/indexreal.php	UNC-Wilm - Coastal Ocean Research and Monitoring Program
COSTA	http://www.aoml.noaa.gov/phod/COSTA/	US- NOAA-AOML; Climate Observing System for the Tropical Atlantic; PIRATA array
DEOS	http://www.coreocean.org/Dev2Go.web?id=208645	US- Academic; Dynamics of Earth and Ocean System; planning vehicle
DMAC	http://dmac.ocean.us/index.jsp	US- OCEAN.US; Data Management and Communication Plan
ECOS	http://www.whoi.edu/mvco/other_data/EC-COO/about.html	US - Eastern Consortium of Coastal Ocean Observatories
ExplorerOfTheSeas	http://oceanlab.rsmas.miami.edu/	RSMAS-RCCL - Explorer of the Seas oceanography lab (cruise ship; Caribbean)
FRONT	http://www.nopp.uconn.edu/	US- Front Resolving Ocean Network with Telemetry;
GCOOS	http://ocean.tamu.edu/GCOOS/gcoos.html	TAMU; Gulf of Mexico Coastal Observing System
GDP	http://www.aoml.noaa.gov/phod/dac/gdp.html	US-NOAA AOML; Global Drifter Program; mixed-layer velocity
GLOS	http://www.glc.org/glos/	US-NOAA; academic; Great Lakes Observing System
GoMOOS	http://www.gomoos.org/	US- Gulf of Maine Ocean Observing System
GSN	http://www.iris.washington.edu/about/GSN/	US- IRIS; Global Seismographic Network
GTSP	http://www.nodc.noaa.gov/GTSP/gtspp-home.html	US-NOAA-NODC; Global Temperature Salinity Project
HOT	http://hahana.soest.hawaii.edu/hot/hot.html	UH- Hawaii Ocean Time-series

HUGO	http://www.soest.hawaii.edu/HUGO/hugo.html	US-UH; Hawaii Undersea Geo-Observatory; geophysics
H2O	http://www.whoi.edu/science/AOPE/DSO/H2O/	US- UH; WHOI; Hawaii 2 Observatory; cabled observatory
IOCARIBEGOOS	http://ioc.unesco.org/goos/IOCARIBE/cari-goos.htm	UNESCO- IO Caribbean region; marine, coastal, ecological data
JIMO	http://jimo.ucsd.edu/	US-NOAA; Joint Institute for Marine Observations
LEO-15	http://marine.rutgers.edu/mrs/	US- Rutgers; Coastal Ocean Observation Lab; Long-term Environmental Observatory
MARS	http://www.mbari.org/mars/Default.html	US-MBARI; Monterey Accelerated Research System; cabled observing testbed
MVCO	http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi	US- Martha's Vineyard Coastal Observatory
NANOOS	http://www.nanoos.org/	US - Northwest Association of Networked Ocean Observing System
NEOS	http://marine.rutgers.edu/neos/	Rutgers; NorthEast Observing System
NeMO	http://www.pmel.noaa.gov/vents/nemo/index.html	US-NOAA; New Millennium Observatory; seafloor observatory
NEPTUNE	http://www.neptune.washington.edu/	US- UW; North East Pacific Time-series Undersea Network Experiments; regional cabled observatory
Neptune CANADA	http://www.neptunecanada.ca/	Cn-US; Neptune Canada; Regional cabled observatory
NC-COOS	http://nccoos.unc.edu/index.html	UNC North Carolina Coastal Ocean Observing System
NVODS	http://www.po.gso.uri.edu/tracking/vodhub/vodhubhome.html	URI - National Virtual Ocean Data System
OceanSITES	http://www.oceansites.org/OceanSITES/	US- Sustained Interdisciplinary Timeseries Environment observing; UNESCO GEO
ORION	http://www.orionocean.org/	US- NSF; Ocean Research Interactive Observatory Networks; ocean observatories
OSCOPE	http://www.pmel.noaa.gov/oscope/	US-NOPP; Oce. Systems for Chemical, Optical and Physical Experiments
openIOOS	http://www.openioos.org/	Open GIS Consortium for oceanographic data
SaBSOON	http://www.skiio.peachnet.edu/research/sabsoon/	US- SkIO; South Atlantic Bight Synoptic Offshore Observatory. Network
SCCOOS	http://www.sccoos.org/	US - Southern California Coastal Ocean Observing System
SCOOP	http://comps.marine.usf.edu/SCOOP/	Ocean.US; SURA Coastal Ocean Observing Program
SEACOOS	http://www.seacoos.org/	Ocean.US South East Atlantic Coastal Ocean Observing System
SECOORA	http://www.secoora.org/	Ocean.us; Southeast Coastal Ocean Observations Regional Association
SFOMC	http://www.sfomc.org/overview2.html	US-SFMOC; South Florida Ocean Measurement Center
S2O2	http://www.bbsr.edu/Labs/hansellab/s2o2/s2o2index.html	US-BBSR; Sargasso Sea Ocean Observatory; planning effort
SEAKEYS	http://www.coral.noaa.gov/sferpm/seakeys/	US-NOAA; Sustained Ecological Research Related to the Management of the Florida Keys Seascape
TBCPS	http://ompl.marine.usf.edu/TBmodel/	US- USFI; Tampa Bay Coastal Prediction System

US COS	http://www.csc.noaa.gov/coos/	US-NOAA COS; NOAA Coastal Observing Systems
VENUS	http://www.venus.uvic.ca/	Cn - Victoria Experimental Testbed Under the Sea; cabled observatory testbed
VOS	http://www.vos.noaa.gov/	NOAA - Volunteer Observing Ship Program
European		
ADRIOCOSM	http://vosdata.santateresa.enea.it:54321/mfs/adri.htm	Part of the Mediterranean Forecasting System; coastal; CTD, XBT
ASSEM	http://geostar.ingv.it/assem.htm	EC; IFREMER; Array of Sensors for longterm Seabed Monitoring of geohazards; geochem
ANIMATE	http://www.soc.soton.ac.uk/animate/index.php	EC UK; Atlantic Network of Interdisciplinary Moorings and Time Series for Europe; CIS, ESTOC, PAP
AUTOFLUX	http://www.soc.soton.ac.uk/JRD/MET/AUTOFLUX/	EC UK; Air-sea flux measurements from VOS;
BOOS	http://www.boos.org/	EC-EUROGOOS; Baltic Operational Oceanographic Network
CLIVAR- Atlantic	http://www.ifm.uni-kiel.de/other/clivar/organization/atlantic/IMPL/data.htm	US-EC; CLIVAR program
DMI	http://ocean.dmi.dk/	EC- Danish Ocean Forecast; Baltic, North Sea, Greenland
EGOS	http://www.meteo.shom.fr/egos/	EC; WMO-IOC; European Data Buoy Cooperation Panel
ESONET	http://www.abdn.ac.uk/ecosystem/esonet/	EC-UK; European Sea Floor Observatory Network; sea floor observatories
EUROGOOS	http://www.eurogoos.org/	EC; European Global Ocean Observing System; 30 members; 16 European countries
EUROSE	http://ifmaxp1.ifm.uni-hamburg.de/EuroROSE/index.html	EC; European Radar Ocean Sensing; hf radars, coastal operational maritime activities
IWICOS	http://www.emi.dtu.dk/research/DCRS/seaice/iwicos/	EC- Integrated Weather, Sea Ice and Ocean Service System
MAMA	http://www.ifremer.fr/mama/	EC- Med Network to Assess and upgrade Monitoring and forecasting
MEDGOOS	http://www.capemalta.net/medgoos/	EC - Mediterranean Global Ocean Observing System
MERCATOR	http://www.mercator-ocean.fr/html/mod_actu/public/welcome_en.php3	EC - MERCATOR project to develop operational oceanography
MERSEA IP	http://www.ifremer.fr/merseaip/	EC- European system for operational monitoring and forecasting of the ocean
MFSP	http://vosdata.santateresa.enea.it:54321/mfs/mfspp.htm	EC - Mediterranean Forecasting System Pilot Project
MFSTEPP	http://www.bo.ingv.it/mfstep/	EC- Mediterranean Forecasting System; Towards Environmental Prediction
NOOS	http://www.noos.cc/	EC-UK Met; North West Shelf Operational Oceanographic System
ODON	http://www.noos.cc/ODON/	EC- Optimal Design of Observational Networks; oce obs North Sea; Baltic
PAP	http://www.soc.soton.ac.uk/GDD/pap/links.html	UK - Porcupine abyssal plan observatory; ecology
SN-1	http://geostar.ingv.it/sn-1.htm	geophysics; abyssal Ionian Sea

Asia/Oceania		
ARENA	http://homepage.mac.com/ieee_oes_japan/ARENA/ARENA-E.html	JAMSTEC; Global marine monitoring with submarine cables
HLTO	http://jpac.whoi.edu/hilats/strategy/moorings.html	JAMSTEC-WHOI; High Latitude Time Series Observatory in the NW Pacific; moorings
JAFOOS	http://www.bom.gov.au/ocean/JAFOOS/contents.html	Joint Australian Facility for Ocean Observing System
NEAR-GOOS	http://ioc.unesco.org/goos/NearGOOS/near-goos.htm	UNESCO-IOC; Near East Asian Regional Goos
OHP	http://eri-ndc.eri.u-tokyo.ac.jp/en/ohp/top.html	U. Tokyo - Ocean network Hemisphere Project; seismology
PI GOOS	http://ioc.unesco.org/goos/Pacific/pacgoos.htm	UNESCO_IOC; Pacific Island GOOS
WAGOOS	http://www.bom.gov.au/wagoos/	Australia; Western Australia GOOS
Other World		
ARGO	http://www.argo.ucsd.edu/	ARGO; Array for Real-time Geostrophic Oceanography; Global array of free-drifting profiling floats; temp, S
CORIOLIS	http://www.coriolis.eu.org/	Fr; System for operational oceanography
GEOSS	http://earthobservations.org/	Global Earth Observing System of Systems
GLOS	http://www.pol.ac.uk/psmsl/programmes/gloss.info.html	GLOS; Global Sea Level Observing System
GODAE	http://www.bom.gov.au/GODAE/	WMO - BOM Global Ocean Data Assimilation Experiment (GODAE)
GOOS	http://ioc.unesco.org/goos/	UNESCO-SCOR- Global Ocean Observing System
GOS	http://www.wmo.ch/web/www/OSY/GOS.html	WMO- Global Observing System
IABP	http://iabp.apl.washington.edu/	UW-APL; International Arctic Buoy Programme
IPAB	http://www.antcrc.utas.edu.au/antcrc/buoys/buoys.html	UTas; International Programme for Antarctic Buoys
ISABP	http://www.dbcp.noaa.gov/isabp/	International South Atlantic Buoy Programme
JCOMMOPS	http://w3.jcommops.org/cgi-bin/WebObjects/Argo	AGO Information Center; geophysical oceanography and marine operations
OSN	http://www.joiscience.org/OSN/OSN.html	JOI-IRIS; Ocean Seismic Network
Seakeepers	http://www.seakeepers.org/	International SeaKeepers; private effort
SOOP	http://www.ifremer.fr/ird/soopip/	IOC-WMO; Ships of Opportunity Program
TAO	http://www.pmel.noaa.gov/tao/	US NOAA PMEL; Tropical Atmosphere Ocean Project; equatorial Pacific buoy array
TRITON	http://www.jamstec.go.jp/jamstec/TRITON/	JAMSTEC- Triangle Trans-Ocean buoy Network; global buoys

APPENDIX 4

Acronyms

AGU: American Geophysical Union

ARENA: Advanced Real-Time Earth Monitoring Network in the Area (Japan)

Argo: Global profiling float project (not an acronym)

AUV: Autonomous Underwater Vehicle

BATS: Bermuda Atlantic Time-series Study

CLEANER: Collaborative Large-scale Engineering Analysis Network for Environmental Research

CLIVAR: CLImate VARIability and Predictability

CoOP: Coastal Ocean Processes

CORE: Consortium for Oceanographic Research and Education

COSEE: Cooperative Ocean Science Excellence in Education

COTS: Commercial Off The Shelf

CUAHSI: Consortium of Universities for the Advancement of Hydrologic Science, Inc.

DART: Deep-Ocean Assessment and Reporting of Tsunamis (NOAA)

DEOS: Dynamics of Earth and Ocean Systems

DLESE: Digital Library for Earth System Education

ENSO: El Niño/Southern Oscillation

ESONET: European Sea Floor Observatory Network

ESSE-21: Earth System Science Education in the 21st Century

GLOBE: Global Learning and Observations to Benefit the Environment

GLOBEC: Global Ocean Ecosystem Dynamics

GOOS: Global Ocean Observing System

GSN: Global Seismic Network

HAB: Harmful Algal Blooms

HighSeasNet: a physical network that connects ships at sea with the Internet via satellite

HOT: Hawaiian Ocean Time Series

IODP: Integrated Ocean Drilling Program

ION: International Ocean Network

IOOS: Integrated Ocean Observing System

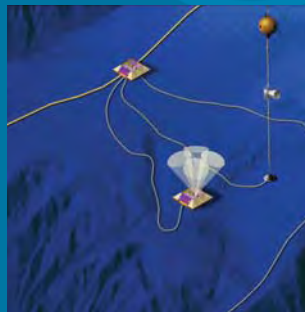
IRIS: Incorporated Research Institutions for Seismology

JGOFS: Joint Global Ocean Flux Study

JOI: Joint Oceanographic Institutions

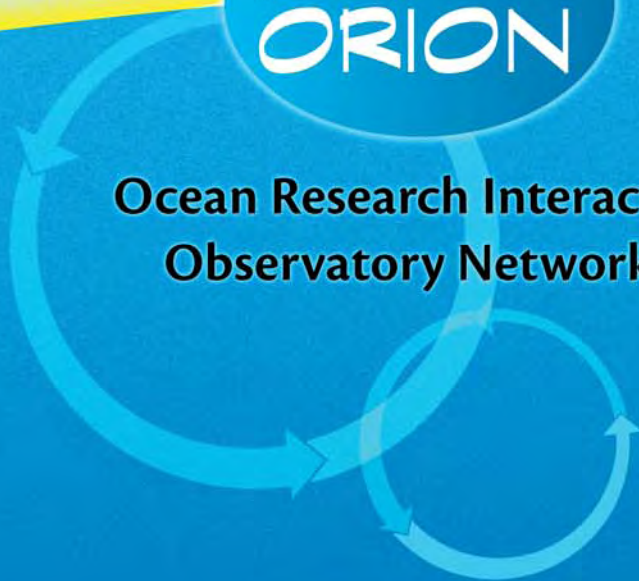
LEO-15: Long-Term Ecological Observatory-15m
MARS: Monterey Accelerated Research System
MATE: Marine Advanced Technology Education
MREFC: Major Research Equipment and Facilities Construction
MVCO: Martha's Vineyard Coastal Observatory
NeMO: New Millennium Observatory (a NOAA program)
NEON: National Ecological Observatory Network
NEPTUNE: North-East Pacific Time-series Underwater Networked Experiments
NMEA: National Marine Educators Association
NOAA: National Oceanic and Atmospheric Administration
NOPP: National Oceanographic Partnership Program
NRC: National Research Council
NSB: National Science Board
NSF: National Science Foundation
OceanSITES: Ocean Sustained Interdisciplinary Time-series Environmental Observation System
ODP: Ocean Drilling Program
OOI: Ocean Observatories Initiative
ORION: Ocean Research Interactive Observatory Networks
OSN: Ocean Seismic Network
REVEL: Research and Education: Volcanoes, Exploration and Life
RIDGE: Ridge Interdisciplinary Global Experiments
ROV: Remotely Operated Vehicle
SOSUS: Sound Surveillance System (Navy)
TOGA-TAO: Tropical Ocean Global Atmosphere Program/Tropical Atmosphere Ocean project (NOAA)
UNOLS: University-National Oceanographic Laboratory System
VENUS: Victoria Experimental Network Under the Sea
WOCE: World Ocean Circulation Experiment

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