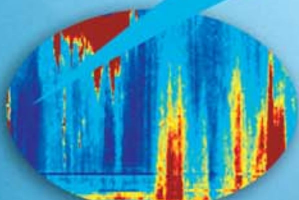
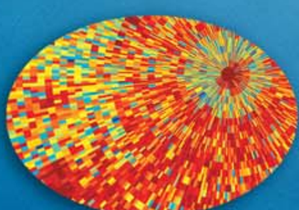
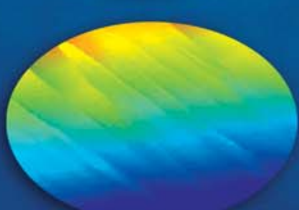
ORION

Ocean Research Interactive Observatory Networks







A Report of the Workshop Held
January 4-8, 2004
San Juan, Puerto Rico

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January 4-8, 2004
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Co-Chairs:
Oscar Schofield, Rutgers University
Margaret K. Tivey, Woods Hole Oceanographic Institution

Contents

I. Executive Summary

The classic problem. *If I were to choose a single phrase to characterize the first century of modern oceanography, it would be a century of under-sampling.* Walter Munk

The vision. *I walk into our control room, with its panoply of views of the sea. There are the updated global pictures from the remote sensors on satellites, there are the evolving maps of subsurface variables, there are the charts that show the position and status of all our Slocum scientific platforms, and I am satisfied that we are looking at the ocean more intensely and more deeply than anyone anywhere else.* Henry Stommel

The new reality. *The ocean sciences are now on the threshold of another major technological advance as the scientific community begins to establish a global, long-term presence in the ocean.* Robert Detrick

The ORION Workshop, held in San Juan, Puerto Rico from January 4 to 8, 2004, brought together 300 scientists, engineers, educators, and science managers to articulate the scientific priorities to be addressed using ocean observatories. Through four days of discussions in fifteen working groups, scientists with a wide range of expertise devised experiments, conferred with engineers on a variety of technical issues, and worked with science educators to formulate an observatory plan that would significantly advance understanding and increase the visibility of the ocean sciences in the coming decades. Working group deliberations are summarized in this report.

ORION will provide high-frequency, continuous, time-series measurements in broad-scale spatial arrays needed to define the links among physical, biological, chemical, and geological variables in the oceans and provide spatially coherent data to study processes and enable modeling efforts. With these attributes in mind, several common scientific themes emerged from the working groups, which are applicable across the wide range of environments and processes of interest:

What role do episodic events play in the oceans? Most researchers readily acknowledge that episodic events, such as earthquakes, volcanic eruptions, algal blooms, and hurricanes can have large influences on oceanic processes. Traditional techniques have not been adequate or effective in quantifying their impact. ORION will provide the tools for making observations prior to, during, and following events, allowing quantification of the roles that they play in processes of interest (e.g., in contributing to mass and heat flux from land to the oceans, mass flux from the ocean surface to the seafloor, sediment transport on continental shelves).

What is the relationship between non-periodic (secular) and cyclical processes in the ocean, and how does this interaction drive observed variability? Many processes in the oceans are subject to annual, multi-year, and decadal cycles. Superimposed on these cycles are secular trends (analogous to the increasing trend in atmospheric CO_2). Defining the relationships and fundamental mechanisms that underlie these cyclical and secular processes in the world's oceans requires ORION's assets, which will allow collection of needed sustained, *in situ* spatial time series.

Do human activities underlie many of the observed changes in the ocean? Humans are exerting an increasingly large influence on the ocean, but the consequences of these activities have yet to be defined. As these human impacts increase they likely will alter natural cycles. Understanding the influence of human activities on the oceans requires understanding the interplay of ocean physics, chemistry, geology, and biology over local and global scales, and over long, continuous time periods. ORION will provide this understanding by collecting spatial and temporal data over a range of scales, and then using these data in numerical models.

In addition to these common themes, scientific groups identified a number of exciting research opportunities that can only be accomplished through use of ocean observatory infrastructure. Examples include: the ability to document Earth's internal structure and dynamics (something currently impossible given the lack of geophysical stations over large portions of Earth's surface); to have controlled access to carry out *in situ* observations and study the deep biosphere; and to determine what mediates changes in biological communities.

The technology group considered a number of issues, including the need to deploy existing workable technology as soon as possible, to develop new sensors and technical capabilities, and to maximize communication and understanding between engineers and scientists. The group's recommendations are to (1) use common engineering methods to develop and operate Ocean Observatories Initiative (OOI) facilities, (2) employ a careful process to permit the engineering community to understand scientific needs, (3) promote collaboration between ORION and the information technology's computer-science community to ensure that the observatories have a truly interactive 24:7 capability for scientists sitting onshore, (4) develop the capability for event response adaptive sampling using ocean observatories, and (5) continue development of sensors and samplers, and integration of instrumentation that can aid communication.

The education and outreach group identified several goals: to increase student and public awareness, understanding, and appreciation of the oceans in the Earth system, and to strengthen science and technology education. Specific recommendations are to (1) enhance communication between researchers and educators, (2) promote the development and diversity of the ocean-related workforce, and (3) stimulate young and old to understand and appreciate the vital role of the ocean in the Earth system, and its importance to well-being.

Challenges. As with all great endeavors, significant challenges need to be overcome. Some of these challenges were identified by the science, education, and engineering attendees in Puerto Rico, and all will require a concerted and proactive effort by the U.S. ORION community. Identified challenges are to (1) vigorously pursue international partnerships, (2) provide an effective voice to help ensure that all ocean-observing efforts for the United States complement and augment one other, (3) develop education programs in parallel with the observatory construction that build upon existing efforts and capabilities, (4) develop a clear and transparent procedure for scientists to gain access to observatories, (5) pursue a system engineering approach for developing the OOI given the scale of the proposed observatory network, and (6) build a management structure that ensures that the scientific community has sufficient control of observatory infrastructure to permit execution of bold and innovative experiments not yet conceived. This last challenge may require changes in funding structure, the proposal process (including proposal review), and institutional reward structures for scientists. Finally, and most importantly, oceanography has had great success with individual and small research groups conducting focused research. As the community embarks on these large interdisciplinary efforts, it must safeguard individual research efforts. The core science budgets at NSF Ocean Sciences must be expanded so that the new ocean observing initiatives do not come at the expense of individual researchers' science activities. The call by the Ocean Commission (http://www.oceancommission.gov) to double the amount of money for ocean research must be vigorously pursued, especially as ocean sciences budgets as a whole in the United States have been stagnant over the last decade.

II. Introduction

"A program of sustained observations is a requirement for understanding oceanographic processes."

Ocean Sciences at the New Millennium, 2001

For centuries, oceanographers have relied on data and observations about the ocean and seafloor below gathered from ships during cruises of limited duration. This expeditionary research approach has resulted in major advances in understanding global ocean circulation, the energy associated with mesoscale circulation, plate tectonics, global ocean productivity, and climate-ocean coupling. These and many other successes have provided exciting glimpses into Earth and ocean processes and have contributed fundamental knowledge for understanding Earth. New enabling technologies now offer the oceanographic community the opportunity to revolutionize the study of the oceans by providing interactive sampling capabilities spanning temporal and spatial scales not effectively captured using ships. To realize the potential of these new observational opportunities, community efforts in the United States (Table 1) have consistently noted that it is critical to develop, deploy, and maintain a permanent, instrumented presence in the ocean; to collect sustained, spatially resolved time-series measurements; and to deliver data back to scientists on land in real time. This sustained presence will complement traditional ship-based research, permitting integrated and adaptive sampling of the world's oceans.

ORION is more than a research program. It is a transformation step, providing scientists, educators, and the general public interactive and continuous access to the oceans. This access will revolutionize our understanding of the ocean and the seafloor below by providing the biological, chemical, physical, and geological information needed to develop a dynamic, three-dimensional understanding of water-column constituents, physical oceanographic parameters, and ecosystems; Earth structure; and fluid and material fluxes within sediments and oceanic crust. ORION data collected at high sampling rates over many years using a variety of sensors on fixed and mobile platforms deployed in key oceanic regions, combined with remote-sensing information, will provide the integrated, time-dependent, scalable picture of the oceans required to distinguish long-term trends or short-term perturbations due to natural phenomena, as well as human-induced changes in the oceans.

The ORION program consists of four main instrumentation components, three of which will be built using Ocean Observatories Initiative (OOI) infrastructure funds from the National Science Foundation's Major Research Equipment and Facilities (MREFC) account.

1. Relocatable deep-sea moored buoys will contribute to studies of the ocean's role in global climate and will help support observations of the structure and dynamics of Earth's interior. These buoys will be sufficiently robust to be able to be deployed in harsh environments such as the Southern Ocean. Moored observatories consist of surface systems that provide central power generation, and data communication by a satellite or radio link to shore. The moored buoys support water-column sensor systems for physical, biological, and chemical studies; seafloor geophysical sensors; and sophisticated flux measurements that quantify the ocean-atmosphere exchange.
2. The regional cabled network will consist of interconnected monitoring sites located on the seafloor. These will span regional-scale (10-1000 km) geological and oceanographic features of a crustal plate. This observatory component will use undersea electro-optical cables connected

Table 1. Some of the many workshops and/or reports that have called for sustained ocean observations. All propose building permanent observing capabilities in the world's oceans.

Workshop and/or Report Title	Year
International Conference on the Ocean Observing System for Climate	1999
Developing Submergence Science in the Next Decade (DESCEND)	1999
Symposium on Seafloor Science	2000
Ocean Sciences at the New Millennium	2001
Integrated and Sustained Ocean Observing System Workshop	2002
Office of Naval Research/Marine Technology Society Buoy Workshop	2002
Scientific Cabled Observatories for Time-Series (SCOTS)	2002
Coastal Ocean Processes and Observatories: Advancing Coastal Research	2002
Autonomous and Lagrangian Platforms and Sensors (ALPS)	2003
Implementation Plan for the DEOS Global Network of Moored-Buoy Observatories	2003
NEPTUNE Pacific Northwest Workshop	2003
Biological and Chemical Instrumentation in the Ocean	2003
Links between OOI and IODP Workshop	2003
REgional Cabled Observatory Network (of Networks) (RECONN)	2003
Technical Issues Related to Cable Re-use	2003
Coastal Observatory Research Arrays (CORA): A Framework for Implementation Planning	2003
Ocean Research Interactive Observatory Networks (ORION)	2004

to shore to supply power, communications, data relay, and command and control capabilities to scientific instruments connected to nodes along the cabled system. These nodes will be designed to interface with moored systems and dynamic observing platforms, such as autonomous underwater vehicles, or floats designed to sample the water column.

3. A network of coastal observatories consisting of long-term arrays spanning continental shelves, augmented with re-locatable instrument arrays, will provide critical measurements to understand along- and cross-shelf transport and transformation processes, to quantify the importance of episodic events in structuring shelf ecosystems (e.g., harmful algal blooms, storm surge, coastal erosion), to improve the accuracy of regional shelf forecast models, and to assess the impact of anthropogenic inputs to and through the coastal zone. Coastal observatories will gather data using moored buoys, shore-based radar, and seafloor cables.

The fourth critical ORION instrumentation component includes deployment of a diverse group of instruments on mobile platforms to provide the spatial context around the fixed time-series point measurements. These mobile assets include fleets of autonomous drifters and vehicles. Spatial data collected by *in situ* ORION assets will be merged with existing and emerging remote-sensing techniques. ORION's success will be measured by how well data from these diverse interactive observational capabilities, and data returned from them, can be integrated into a fully four-dimensional picture of the ocean system.

The 2004 ORION Workshop

Many of the technical elements of proposed observatories have been highlighted at workshops focused around specific technologies. For example, the Scientific Cabled Ocean Time Series (SCOTS) workshop focused on scientific issues that could be addressed using seafloor cable networks (Glenn and Dickey, 2003), while the Autonomous and Lagrangian Platform and Sensors (ALPS) workshop focused on the utility of mobile vehicles and drifters (Rudnick and Perry, 2003). Although these focused planning efforts were needed to identify critical technical and scientific issues, and to exchange ideas within specific communities, they did not allow for effective communication of information across groups, or for coordination of a large-scale strategy for ocean observatories. This compartmentalization was also mirrored in the scientific planning efforts, with different workshops focusing on different spatial scales (e.g., global, regional, coastal).

As a first step in defining the ORION scientific, technological, and educational priorities, the Dynamics of Earth and Ocean Systems (DEOS) Steering Committee, with support from the National Science Foundation (NSF), convened an open community workshop in early January 2004 in San Juan, Puerto Rico. Over 300 scientists, engineers, educators, and science managers from eight countries attended the meeting (Appendix 1). Compared with past workshops, participants were not constrained by a specific scientific focus (e.g., solid Earth, air-sea fluxes, or marine food webs), geographical footprint (e.g., coastal, regional, or global), or observational platform (e.g., cables or autonomous underwater vehicles). Prior to the workshop, participants had web access (still available at www.orionprogram.org under "San Juan Workshop") to the agenda (Appendix 2), background information papers, and an evolving list of scientific questions that would be discussed by various groups during the workshop.

The first day of the ORION workshop was devoted to science, technology, and education overview talks, a poster session (Appendix 3), and a panel discussion of broader ocean-observing activities with representatives from the National Science Foundation, the National Oceanic and Atmospheric Administration, the Office of Naval Research, Ocean.US, and the National Aeronautics and Space Administration.

The remainder of the workshop focused on highly interactive small-group discussions of science, technology, engineering, and education and outreach. The relatively large (>35 participants) technology and education and outreach groups had dual tasks: to send pairs of educators or engineers to join and participate in science small-group discussions, and to periodically reconvene to tackle technology or education and outreach issues that arose during the scientific discussions. The goal was to weave technology and educational opportunities into the initial observatory network design.

The smaller scientific working groups, all with fewer than 30 participants, met to discuss how access to two-way communication, sustained data recording, and power could be used to tackle questions related to Earth structure, plate dynamics, fluid-rock interactions, air-sea fluxes, biogeochemical cycles from rivers to the continental slope, benthic water-column coupling, global ocean circulation and climate, global biogeochemistry, small-scale mixing and nearshore processes, marine food webs, impact of humans on marine ecosystems, and marine ecology. The groups were encouraged to mix and evolve the scientific focus as desired. These groups were asked to identify, among other items: (1) the most exciting research opportunities that could be provided by ORION but could not be addressed using traditional assets and techniques, (2) the spatial and temporal scales required, (3) the priority measurements and parameters needed, (4) the education and outreach opportunities, and (5) a time line for addressing the question or experiment (Appendix 4).

This report summarizes working group deliberations. In some cases, working group materials have been combined to reduce redundancy.

III. Working Group Reports

A. Benthic-Pelagic Coupling

Paul Snelgrove (Moderator), Peter Jumars (Rapporteur)

Coupling between pelagic and benthic ecosystems directly affects the biogeochemical cycling of elements in the oceans and the micro and macro ecology of marine ecosystems. It also determines the potential of the oceans to sequester material over millions of years. Benthic and pelagic systems are linked through myriad biological, physical, and geological processes that operate over multiple spatial (centimeters to thousands of kilometers) and temporal (minutes to decades) scales. Some of the important processes include primary production in the overlying pelagic system, and events such as volcanic-tectonic-sediment transport (e.g., slumps, erosion events, and ice scour), creation of vent and seep habitats and plumes, and release of gas hydrate (degassing and big events). These events can have dramatic consequences for pelagic ecosystems on time scales similar to the events, and over far longer time scales (e.g., hundreds of years) for benthic ecosystems. Nonetheless, our understanding of these events, and therefore our predictive capacity, is limited because conventional ship-based sampling programs are ill-suited for capturing much of the variability inherent in benthic-pelagic coupling. These "aliasing" issues could be rectified by data collection at very high sampling rates over periods of days for some ecological questions or decades or longer for others. Nearly continuous data would provide a strong statistical basis for understanding events, from tidal forcing to decadal oscillations. Additionally, if data were collected over several biogeographic regions of the ocean, they would provide a useful framework for comparing and contrasting a range of ecosystems.

Scientific Priorities

1. Determine the spatial and temporal coherence scales of benthic-pelagic coupling.
2. Determine how the benthic ecosystem reflects the pelagic ecosystem, and the mechanisms by which the pelagic ecosystem structures the benthic ecosystem.
3. Assess the importance of episodic events versus seasonal processes in structuring benthic-pelagic interactions.

The OOI infrastructure will collect contemporaneous measurements of the physics, chemistry, and biology of both the benthic and pelagic ecosystems. Frequent measurements will be made at a variety of depths, providing the possibility of quantifying particle fluxes and their corresponding impact on the redox state of the benthic community, which has been universally problematic to capture.

Example ORION Experiments

How important are episodic versus seasonal pulses of pelagically derived organic carbon to benthic communities?

Benthic communities rely on varied combinations of *in situ* production and export of organic carbon from the pelagic ecosystem for food. Production of organic carbon in the pelagic ecosystem reflects seasonal events, such as the spring bloom, and short-lived, episodic blooms. Although satellites can provide estimates of pelagic productivity, how much of that organic material reaches the seafloor remains an open question. Efficiency of carbon export to the benthos is a function of the composition and size of sinking material and the degree to which material is remineralized during downward transport. Although seasonal pelagic productivity dynamics are important, recent discoveries of massive, discrete (in space and time) phytodetrital aggregates reaching the deep sea suggest that large, episodic blooms may be critical in the formation of large aggregates capable of reaching the seafloor in the face of efficient remineralization processes in the water column. In multiple areas of the world, relatively intact phytoplankton aggregates have been found in thousands of meters of water. For benthic-pelagic coupling, this is tremendously important as the efficiency of the export production determines the food quality and quantity, biogeochemical responses, biogeochemical cues for benthos, migratory responses (horizontal and vertical) of species that may move large distances, reproductive responses, and responses and energetics of the hyperbenthos, while influencing the patch structure of the benthos.

To quantify export of organic carbon to the benthos, ORION will provide arrays of instruments and stationary sensors together with mobile platforms in a range of deep-sea, continental-slope, and shelf locations. Networks of broadband acoustic arrays and bio-optical sensors will allow scientists to detect bloom events. Sediment traps could then be triggered, allowing organic material associated with episodic events to be characterized. Complementary sensors will characterize changes in the flow rates, physical properties, chemistries, and microbial compositions surrounding the traps. Stationary camera systems will record the evolving impact of the events on benthos and macrofauna. Surveys by instrumented benthic rovers or autonomous underwater vehicles (AUVs) could assess spatial heterogeneity in the organic flux measurements. Combined with surface productivity measurements, estimates of the remineralization efficiency for the pelagic ecosystem could be constrained. From a biological perspective, phytoplankton composition and abundance can be measured with multispectral fluorometry and other optical approaches, such as HPLC (high-performance liquid chromatography) and flow cytometry. Light-quality measurements are well within the domain of existing optical technologies. Zooplankton can be enumerated with video plankton recorders, isokinetic pumping (e.g., moored automated serial zooplankton pumps [MASZP]), and multi-frequency acoustics; because many of these sensors are small, they are easily transferable to AUVs to provide spatial representations. Mobile benthic megafauna and demersal fauna can be enumerated with acoustics and photography. *In situ* genetics and enzyme scans are emerging technologies that should allow some taxonomic resolution. Chemistry is a key aspect of benthic-pelagic coupling, particularly as it relates to carbon and nutrient cycling. Current or nearly ready technologies include flux probes and sipper cores to measure and/or profile oxygen, methane, and sulfide, atomic absorption, *in situ* CHN (carbon, hydrogen, nitrogen), dissolved organic carbon, dissolved CO_2, dissolved inorganic carbon, and alkalinity. Physical and geological measurements that have direct impacts on benthic-pelagic coupling include currents, temperature, turbulence, granulometry, concentration of suspended sediments, micrography, particle concentration (including living particles and their pigments), acoustic properties of the ocean bottom, and sediment transport and seepage (e.g., groundwater and methane). Most of these bi-

Box 1. Time Series Provide Power in Estimation and Experimentation

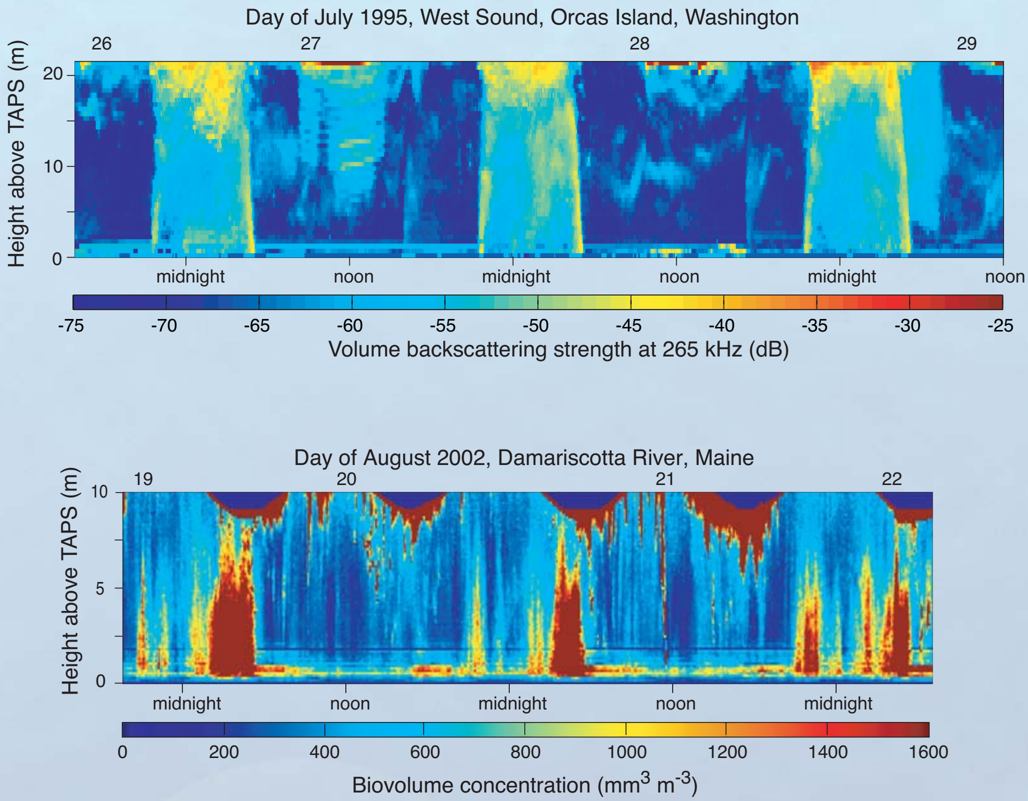
Contributed by Pete Jumars, University of Maine

Long, continuous, multivariate, high-frequency time-series observations provide statistical power. Over time, any two variables with trends are correlated, but their correlation may provide little insight. Regularly spaced, multivariate observations readily apply methods that remove such spurious correlations. One popular approach is to work with the change in each variable between observation times rather than with the raw observations. This method asks whether a change in one variable is associated with a change in another.

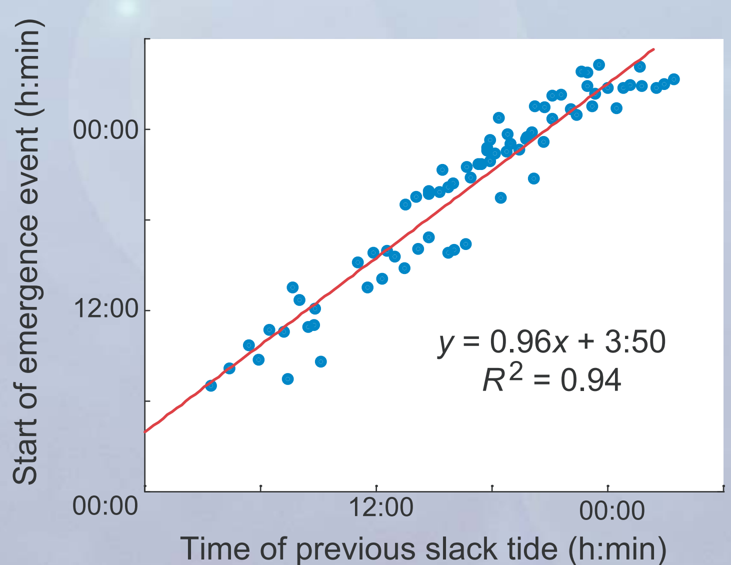
The power that cabled, high-frequency, continuous time series provide for model estimation is dramatically demonstrated by two examples. One is a continuous time series of oxygen concentration at multiple heights above bottom, coupled with turbulence-resolving 3-D velocities. A turbulent eddy-flux approach can provide continuous estimates of vertical flux of oxygen and of any other solute whose concentration can be measured with high temporal resolution (Berg et al. 2003). Over much of the continental shelf, oxygen can evolve from benthic microalgae during daylight, with net uptake of oxygen during the night. Twenty-four-hour running means of efflux from the seabed estimate daily net oxygen evolution and thus estimate net autotrophy or heterotrophy of the system. This robust approach is insensitive to many artifacts of traditional incubation methods. It integrates both diffusive contributions through the diffusive sublayer and advective contributions through animal respiratory pumping. Additional power in understanding benthic production comes from combining oxygen flux time series with spectral irradiance time series to further constrain benthic primary production. Oxygen is a master governing variable for sediment geochemistry, so its net fluxes and concentrations are fundamental to overall understanding of time variation in sediment geochemistry.

A second example is multi-frequency, upward-looking, range-gated acoustic backscatter. At present, it is feasible in cabled mode to collect time series at multiple frequencies that allow estimation of biovolume (mm^3 of organisms m^{-3} of water) every minute in every 12.5 cm depth bin above the bottom (to heights of 200 m above bottom for the lowest frequencies). Acoustic inversion produces biovolume estimates. In areas of the Puget Sound and of the Damariscotta River estuary, Maine, animals leave the seabed nightly and enter the water column (figure, top). In both regions, the biomass of emergent animals exceeds by an order of magnitude the water-column integrated biomass of zooplankton and so is key in any evaluation of benthic-pelagic coupling. Dominant animals in both cases are mysid shrimp of ~1 cm length that are notoriously difficult to capture by traditional sampling methods. Moreover, their movements through the water column are sufficiently rapid that traditional means cannot quantify these vertical group velocities that are easily estimated acoustically. Time-series analysis further reveals two peaks of migration in the more macrotidal East Coast estuary (a fjord with little freshwater input), one near the 24-hr period that is evident in the daily pattern, but another at 12.4 hr coincident with the M2 tidal period. The principal emergence event in the Maine estuary occurs at a constant phase of the tide (figure, bottom).

Multiple instruments sampling simultaneously are beginning to resolve questions of coherence. Emergence at deeper sites leads emergence at shallower sites; animals that have farther to go leave sooner. Timing and vertical distribution details are key to benthic-pelagic coupling in at least two ways. Mysid shrimp are notoriously voracious omnivores of phytoplankton and smaller zooplankton, but they are themselves a favored food of juvenile fishes. Reflecting the trade-off, these migrations halt abruptly when the risk of predation is not counterbalanced by the reward of high food availability in the plankton. Seabed observatories also can add statistical power in resolution of experimental manipulations or of consequences of particular events. The technique of "intervention analysis" (Box et al., 1994) fits explicit time-series models to observations prior to a manipulation or intervention. The best-fit model is then applied to the continuing time series after the manipulation or event, with the residuals resolving the treatment effect. To date, marine applications have been limited by bandwidth and power (Self et al., 2001).



False-color time series plots of volume backscattering strength at 265 kHz (upper panel; Kringel et al., 2003) and multi-frequency estimated biovolume (lower panel; Taylor et al., in review) as a function of height above the acoustic instrument (TAPS-6) used to record backscatter. The series have been aligned to emphasize nightly emergence events. Note that the biggest events of the night happen well after dark at the Maine site and begin on the first deceleration of the tides after dark. Red regions near the top of both panels are artifacts of reflection from the air-sea interface, combined with some bubble entrainment and fish activity. At both sites group migration speeds can be estimated by regression on features evident in these plots.



Algorithmically determined initiation times of the large emergence events in the Damariscotta River estuary (Taylor et al., in review). These data are from the spring through the fall of 2001 and 2002. The slope near unity indicates constant phasing, with initiation near the time of initial deceleration. Although the largest events occur at night, smaller emergence events occur also during the day at the same tidal phase. Transmissometry and the phasing both reject an alternative interpretation as sediment resuspension. Comparable data would be impossible to obtain without cabled observations.

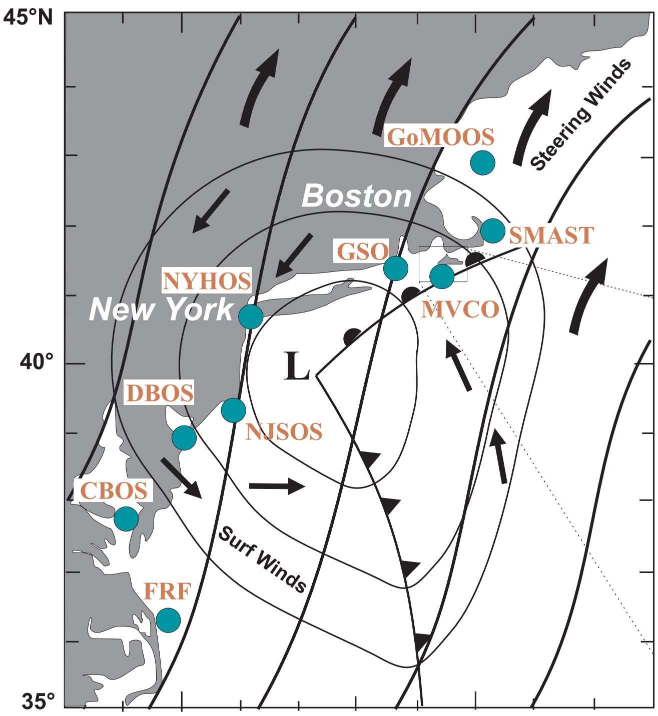


Figure A-1. Map indicating a typical extreme storm track across the northeastern United States and the locations of ocean observatories that could be enhanced as part of the ORION program.

ology, chemistry, and geophysical sensors and instruments are off-the-shelf technologies and will be a critical part of the maturing ORION network.

How important are major storm events in influencing benthic-pelagic coupling?

Storms influence benthic-pelagic coupling through sediment resuspension and deposition, phytoplankton production response, export of organic material to the benthos, increased nutrient efflux from sediments, recruitment responses, and disturbance effects on benthic communities. Documenting these responses, however, has been difficult as data are rarely collected before, during, and immediately after large storms.

ORION will provide the infrastructure to quantify the importance of the storms over regional scales. One experiment might focus on hurricanes and tropical storms that track up the eastern seaboard of the United States and into Canada along a network of continental shelf observatories (Figure A-1). Regional responses of currents, turbulence, sediment resuspension, and benthic chemical-biological state could be documented with stationary acoustic-optical arrays to provide continuous measurements. Impact of the storm on benthic redox state could be recorded with placed probes from the sediment-water interface to below the anoxic zones. Response along the northeast storm track would allow researchers to assess the influence of local effects set up by coastal topography and of modification to air-sea exchange due to the influence of limited fetch, bottom friction, and bottom topography on both the wave and current fields. Stationary camera systems would record evolving impacts of the event on the benthos. These time-series measurements could be used to improve atmospheric and oceanic forecasting, and provide the database to enable development of coupled physical/biological models (including storm track, severity, and direct and indirect effects) that could predict ecosystem effects from the tropics to the subarctic. These data could be complemented with manipulative experiments such as particle labeling to study bioturbation and respiration rate changes after experimentally or naturally induced disturbances.

Issues to Resolve

A key issue with observatories is the potential artifact the observatory might create by becoming an artificial reef that will attract organisms (Figure A-2). A second issue is spatial coherence (i.e., what area does the mooring represent and what are the boundaries?). Microelectrodes measure only diffusive flux and flux chambers are problematic without relocation; particularly promising for those chemical species with fast-response sensors is the recent innovation of eddy flux estimation. Exhaustive site surveys are needed to evaluate the representative nature of the observatory locale and the scales of spatial variability. In addition, there is currently no technology that would allow recovery of cores or automated, non-destructive identification of organisms, both in the water and in the seabed. Optical and acoustical technologies do not provide species-level identification that is necessary for some ecological questions. Individual observatory locations cannot resolve issues of spatial variability and coherence and may not be representative of broader regions; "extension cords"

Box 2. Education Scenario: What Lives in the Mud?

Contributed by Janice McDonnell, Rutgers University

Students in eighth grade science classes in across the country collect benthic samples from local ponds, wetlands, or coastal ocean environments shortly after the school year commences. When their field work is done, the students go back to their classroom to complete sample preparation and see what they have collected. To help them identify organisms and to compare their set of critters with those from other states and countries, they go to their classroom computers to access the web-based resource, "What Lives in the Mud?" developed by ORION scientists and educators. The web pages include a reference link to help students identify taxa, and an "Ask an ORION Scientist" area where students can ask questions of scientists if they cannot find the answer on the "Frequently Asked Questions" part of the web site.

ORION scientists interact with teachers and their students at key points throughout the school year by posing a series of "concept questions." These questions are based upon authentic observations and data, and will help students connect their research with that of ORION scientists. The discussion generated between the scientists and the students is moderated by an informal education specialist and is designed to model good science and exemplify the thinking/questioning process that scientists use in their work.

As part of the project, teachers work through a series of web-based lessons with their students to help reinforce the spirit and objectives of the "What Lives in the Mud?" project. These lessons connect students to the big-picture science themes and concepts that the ORION research supports, such as a more in-depth understanding of carbon cycling. These lessons address the National Science Education Standards and AAAS Benchmarks: Flow of Matter and Energy (Chapter 5, 8^{th} grade standard).

The main focus of this collaborative project is for students to go frequently to the discussion area of the web site where they post their findings and read reports from other classes from around the country. Through interpersonal exchange, students can collect, analyze, and share original information and gain access to data and resources they would otherwise not have in a traditional classroom. Examples of these types of projects can be found at the Center for Innovation in Engineering and Science Education at www.k12science.org.

are therefore important to resolving many science questions, though there are alternative approaches (e.g., multiple ship surveys) that can also help to resolve this question.

Outreach

The benthic observations and experiments outlined above can provide meaningful learning experiences for diverse communities. These communities may include a wide range of stakeholders such as K-12 teachers, students (K-16), resource managers, resource users, and underrepresented groups in the marine sciences. The benthic biological observatory data provide new and innovative opportunities to improve public understanding of physical data and their interrelationships to the living ecosystem. The following examples are offered to define the range of educational opportunities associated with benthic-pelagic coupling research:

Formal Education: Scientists and educators will work together to develop Internet-based materials where students will be encouraged to collaboratively generate data, seek patterns, and develop simple scientific models that have predictive power. Our goal is to improve student understanding of scientific concepts such as the carbon cycle from a "two-dimensional" picture of ideas to a more scientific viewpoint of a model (i.e., an idea that is used to explain/predict data).

Informal Education: ORION scientists could partner with an informal science learning center/ museum or aquarium to develop educational products (e.g., exhibit, program) that mines and manipulates georeferenced biological data to understand temporal change in living systems.

Informing Policy: The opportunity exists for ORION scientists to work with emergency management officials to improve public awareness and response to storms. ORION sci-

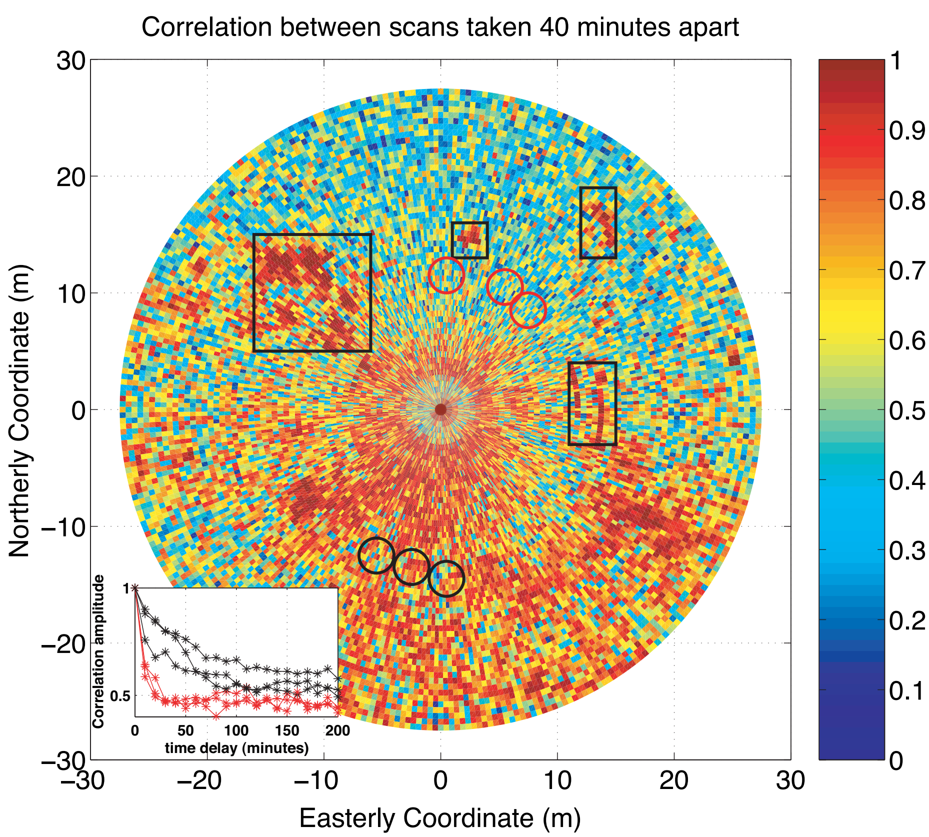


Figure A-2. A known problem with placing equipment on the seabed is the so-called "reef effect." Objects on the bottom attract fishes and crabs as well as longer-term settlement by suspension feeders that, in turn, enrich the surrounding sediments through biodeposition. Fishes (as in this data set from 20 m depth in coarse sands of the Gulf of Mexico) can be major sources of sediment bioturbation. This sector-scanning sonar "correlation" image allows definition of the temporal and spatial extent of such artifacts. The larger figure indicates decorrelation as a function of distance away from bottom-deployed structures (shown enclosed by rectangles—the smallest rectangle is for a stereo camera deployed to examine biological activity). The inset shows correlation in backscatter as a function of time both near and away from the stereo camera; red (black) lines correspond to red (black) circles where average correlation is calculated. Figure courtesy of Kevin Williams, University of Washington, Seattle.

entists should develop strong partnerships with the coastal management community to optimize the applications of observatory data to coastal decision making.

The Key to Success: Observatories will be successful if investigators are able to bypass territoriality and focus on mechanistic research. Initial successes and collaborations will entrain international access. Funding agency flexibility will expedite the initiative and research output. Ease of use, standard interfaces, and access to regional and technical representatives will make ORION a community asset. Information sessions at scientific meetings will also help to engage potential users. Efforts to embrace educators at all stages of development will garner greater public support and interest.

Benthic-Pelagic Coupling Working Group

- Fred Grassle, Rutgers University
- Peter Jumars, University of Maine at Orono
- Janice McDonnell, Rutgers University
- Anna Metaxas, Dalhousie University
- Graham Shimmield, Dunstaffnage Marine Laboratory
- Paul Snelgrove, Memorial University of Newfoundland
- Carrie Thomas, North Carolina State University

B. Biogeochemical Cycles

Francisco Chavez (Moderator), Mark Moline (Rapporteur)

The Joint Global Ocean Flux Study (JGOFS) was an international program designed to better understand the ocean carbon cycle (see box on p. 16). The program had two components: (1) process studies in important areas of the world's oceans (North Atlantic, Equatorial Pacific, Arabian Sea, Southern Ocean) and (2) time-series efforts in northern hemisphere subtropical gyres (Bermuda, Hawaii). One of the shortcomings of the first component was unveiled by the second: significant year-to-year variability is evident in all areas of the world's oceans, including the subtropical gyres. Fixed-point observatories are uniquely suited for fully sampling two of the four dimensions (time and vertical) at high resolution and will complement other ORION elements. A global presence of long-time-series sites in key geographic regions around the globe will provide highly detailed observations of atmospheric processes just above the sea surface in addition to oceanographic measurements from the seafloor to the sea surface for a wide number of variables.

It has become clear that environmental variability plays a major role in atmospheric and oceanic circulation, biogeochemical cycling of elements in the ocean, and the abundance of ocean living resources. It has also become clear that unraveling the influence of natural environmental variability requires a concerted global effort. For example, changes in the abundance of sardines off Japan are clearly linked to changes in this same species in the northwestern and southwestern Pacific and the southwestern Atlantic. These changes are likely driven by observed changes in ocean circulation and atmospheric forcing.

A review of ocean time-series research shows that an individual or institution has been the primary motivator. When the individual either runs out of resources or interest, the time series typically comes to an end. Because of the very real possibility that humans are inducing changes in climate and ocean circulation, sustained long-term measurements are critical for determining the extent and consequences of these changes. This need emphasizes the importance of continuing existing efforts and beginning others like ORION as soon as possible—as a global network rather than a collection of PI- or institution-driven projects. Coordination, support, advocacy, and facilitation of by programs such as CLIVAR, GOOS, and POGO are therefore essential.

Scientific Priorities

1. Determine how changes in basin-scale forcing affect the dynamics of the North Pacific Drift Current and how these dynamics affect the nutrient and carbon trapping capacity of the California Current System.
2. Understand the imbalance between nitrogen fixation and denitrification (the marine nitrogen cycle) and its relationship to the ability of the oceanic biological pump to sequester anthropogenic carbon dioxide.
3. Quantify how regime shifts interact with seasonal and stochastic variability to produce extreme events such as the recent coccolithophorid bloom in the Bering Sea and the basin-scale hypoxia.

The challenge of collecting continuous time series in critical areas is formidable because the oceans are a vast and hostile environment, only the surface is accessible with space-based remote sensing, physical and biogeochemical parameters are linked, and an extreme range of spatial and temporal scales (meters to thousands of kilometers, hours to decades) need to be covered. Fortunately, new mooring and instrumentation technology make it possible now to effectively deploy and maintain unmanned observatories that will autonomously carry out diverse measurements over extended time periods while providing much of the data via satellite in near real time. Moorings have relatively large payloads and can be equipped with battery packs or power generators, making them well-suited to support an array of sensors and instruments from users in diverse disciplines. Moorings can have instruments at the sea surface, throughout the water column, and on the seafloor. This attribute makes moorings a key resource for observing cause and effect (e.g., between surface heat loss and sinking of surface water) and interrelationships between diverse fields of study (e.g., between upper-ocean mixing and the phytoplankton bloom). Moorings are also uniquely suited for sampling critical or adverse regions and periods (e.g., straits, boundary currents, boundary layers, ice-covered regions, storm seasons). ORION will help fill the void for time series in the overall global observation system. It will provide unique scientific contributions, encourage innovative technology solutions, and pave the way forward to integrating the science across many disciplines.

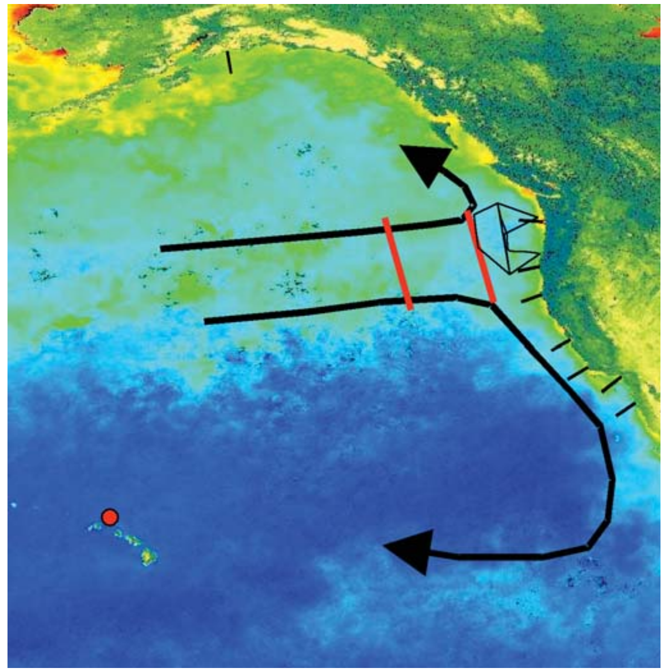


Figure B-1. One suggested ORION kick-off experiment is to study the West Wind Drift and its role in ocean carbon dynamics. The arrays would consist of moorings augmented with AUVs and drifters. The goal would be to understand the dynamics in the California current and how it is modulated by low- (PDO, ENSO) and high-frequency events (storms). Figure courtesy of Mark Moline and Francisco Chavez.

An Example ORION Experiment

How do changes in basin-scale forcing affect the dynamics of the North Pacific Drift Current and how do these dynamics affect the nutrient and carbon trapping capacity of the California Current System?

Studies of basin-scale coupling have traditionally relied on statistical analyses rather than direct measurements. These linkages are characterized by large spatio-temporal scales, although the actual mechanisms may be associated with mesoscale and smaller-scale dynamics and events. Processes such as the Pacific Decadal Oscillation have been inferred from long time series, but the associated dynamics and their impacts on other components of the ocean system are not known. The ORION project will support the necessary measurements to study these processes. Specific questions include:

- How will shifts in wind forcing affect the North Pacific Drift Current with regard to its position and intensity?
- How do these changes affect the southward penetration of Subarctic Pacific waters into the California Current System (CCS) and the northward flow of the California Undercurrent? What are the associated mechanisms?
- What are the linkages with the dynamics of the Subtropical Gyre?
- What are the impacts of these processes on oxygen concentrations and subsequent impacts on primary productivity/respiration and biogeochemical cycling and fluxes?

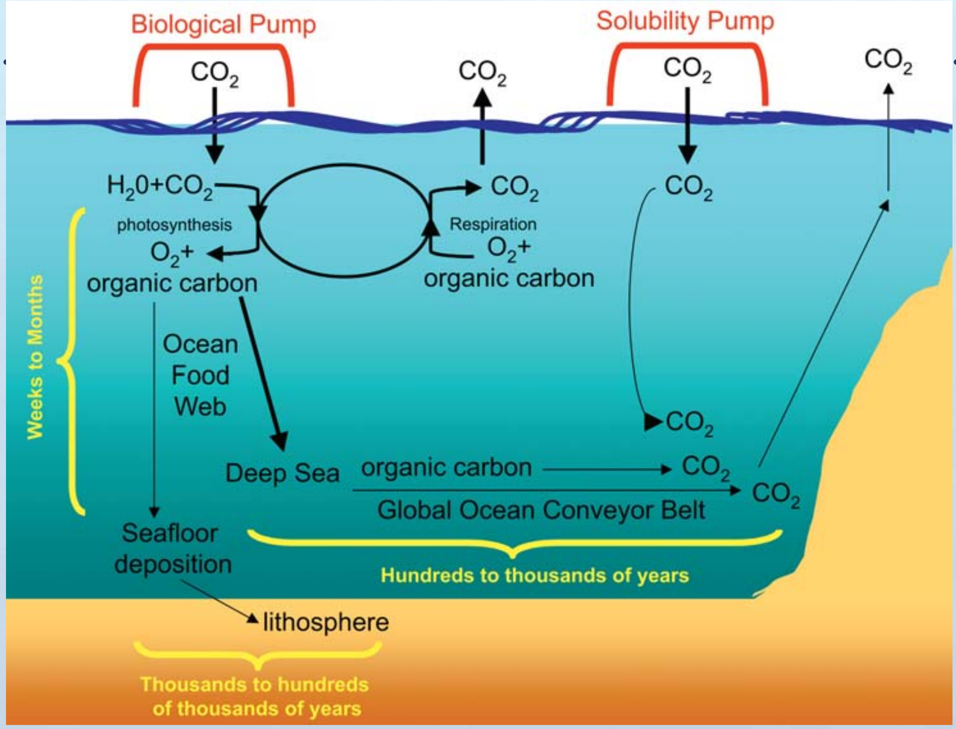
Box 3. Global Ocean Carbon Cycling: Questions After JGOFS

Contributed by Paul Falkowski, Rutgers University

One of the most striking climatic patterns that emerged in the 20th century was observation of the concentration of atmospheric CO_2. The decadal record of carefully measured and calibrated atmospheric values revealed two major signals: an annual oscillation (i.e., a seasonal cycle) in which CO_2 increased during the northern hemisphere winter. That cycle rode on a long-term (secular) trend of increasing concentration of the gas. Atmospheric scientists and terrestrial ecologists realized that the cycle was primarily driven by the uptake of CO_2 by terrestrial vegetation during the growing season in the northern hemisphere. After considerable investigation, primarily focusing on gases trapped in ice cores, the long-term trend has been clearly shown to be largely due to the combustion of fossil fuels. The cyclical pattern is natural, and shows variability related to droughts, fires, and climate patterns. The latter is now known to be embedded within a much longer (100,000 year) cycle that has been altered by human activities and has been driven by industrialization, economic development, and human population growth. Thus, there are cycles within trends within cycles. Clearly, observing the annual cycle for one or two years would not have revealed the trend. Despite the heroic efforts at the Bermuda Atlantic Time Series (BATS) and Hawaiian Ocean Time Series (HOT), equivalent time series in are lacking to ascertain similar processes in the world's oceans.

The response of the atmosphere to changes in CO_2 emissions is virtually instantaneous as it has no buffering capacity for CO_2, and the gas mixes relatively rapidly throughout the globe. But the atmosphere is a corridor between two larger reservoirs: the oceans, which contain about 50 times more carbon primarily in inorganic forms, and terrestrial ecosystems, which hold about three times as much carbon—all in organic form. The capacity of the oceans to absorb CO_2 is enormous—and the oceans ultimately (on millennial time scales) will be the major repository for all the anthropogenically produced CO_2. The exchange is mediated by two phenomena. The "solubility pump," which appears to be a dominant mechanism, is driven by physical circulation and inorganic chemistry (see figure). The distribution of pCO_2 in the surface waters of the world's oceans is extremely patchy, and the rate of diffusion of the gas is primarily related temperature, which controls the solubility of CO_2. The second mechanism by which CO_2 exchanges with the ocean is via biological carbon fixation, which produces particulate organic carbon. Upon sinking into the ocean's interior, the organic matter is reoxidized to inorganic carbon through respiratory activity. This process is unlike terrestrial ecosystems where carbon can be stored directly as biomass (mostly trees), and as organic matter in soils. Oceanic photosynthetic biomass amounts to less than 0.5% of the terrestrial biomass; however, the flux of organic carbon in marine ecosystems is fully 45% to 50% of the global total. Hence, oceanic ecosystems have very high carbon turnover rates but on time scales of thousands of years. During this thousand-year time period, the export of oceanic productivity to the interior will change due to prevailing climate patterns. Therefore, climate change will likely alter the sequestration and transformation of carbon in the oceans; however, the corresponding feedbacks on global biogeochemistry remain an open question. Spatial time series are critical for understanding these processes.

Changes in the ocean carbon cycle will be driven by changes in the prevailing nutrient profile of the ocean. There are generally four pathways by which biological carbon fixation can influence net carbon exchange between the atmosphere and ocean: (1) changing the nutrient inventory of the ocean—specifically adding or removing a nutrient that limits primary productivity, (2) utilizing nutrients that are in excess in surface waters more efficiently—these areas are called high nutrient/low chlorophyll (HNLC) regions, of which the Southern Ocean is the most critical, (3) altering the ratio of the sinking flux of particulate organic carbon (POC) to particulate inorganic carbon (PIC)—this process is dependent on the production of PIC in surface waters, which is, in turn, dependent on groups of specific organisms, and (4) altering the elemental composition of organisms will directly impact the efficiency by which carbon is exported to the deep sea.



The ocean's carbon cycle and how carbon cycling is regulated by the solubility and biological pumps.

Long-term (secular) trends in net exchangeable production remain to be elucidated. Of the four basic processes mentioned that are critical to influencing this flux term, three are accessible, either directly or indirectly, from space and subsurface technology available today; however, rarely are these assets deployed for long-term time series. A time series of decades will be required to understand the major biological sinks of carbon shrink or grow, and why. Fixed inorganic nitrogen appears to be one of the major macronutrients limiting productivity in much of the world's oceans. Carbon cycling is also sensitive to the phytoplankton taxa present. For example, some nitrogen-fixing cyanobacteria can influence nitrogen levels, and calcite-precipitating organisms (coccolithophorids) can influence the export flux efficiency. Understanding these processes requires fundamental research in bio-optics, biochemistry, and biophysics. Combining remote-sensing data with ocean-observatory data provides the 4-D data required to move ocean carbon cycle science forward. Given this, there are several ways to move the science forward:

- **Collect long-term observational data sets.** Documenting change and determining its cause requires long-term data sets that can be validated and compared to ensemble global biogeochemical models.
- **Adopt an integrated ocean-observing approach that combines subsurface ocean-observing assets and remote-sensing technologies.**
- **Expand the *in situ* network of sensor calibration sites to accelerate the development of products that can be measured from space.** The emerging *in situ* observational systems, including gliders, moored instruments, and autonomous remotely controlled vehicles, are potentially powerful platforms that, in conjunction with space-based and fixed-wing observations, will lead to extraordinary discovery and insight into biogeochemical cycles in the oceans. SeaWiFS and MODIS use the Marine Optical Buoy off Lanai, Hawaii as their primary vicarious calibration site. A network of relatively inexpensive calibration sites should be a central component to ORION infrastructure.
- **Continue support of community-wide technical enabling activities.** Much of the success of the SeaWiFS program in providing high-quality derived products was a result of calibration round robin, measurement protocol development, community bio-optical database, and *in situ* instrument development and evaluation activities. These activities have been primarily supported by the SeaWiFS and SIMBIOS Projects, which ended in 2003. Such a strategy should be adopted by the ORION science community.

- Do these changes shift the CCS from a source to a sink of atmospheric CO_2?
- How do these processes affect ecosystem structure in the Subtropical Gyre? Do they control the balance between nitrogen and phosphorous regulation of primary productivity on interannual time scales?
- Ultimately, how are these changes in forcing linked with basin-scale oscillations such as the PDO?

The focus of this experimental effort is to understand the dynamics of carbon. The proposed network consists of an array of moorings (roughly 30) ideally spanning ocean basins that would monitor basin biogeochemical budgets (Figure B-2). We would start by deploying several dense arrays in areas of high biogeochemical importance. These dense mooring arrays will be augmented with autonomous platforms such as Lagrangian drifters. These platforms will better address the transformation of materials by providing the spatial data sufficient to resolve the scales over which many of the transformation rates occur. Data from these arrays will be able to track critical-rate processes such as oxygen decreases and nitrification/denitrification. Combining subsurface time series with satellite imagery will allow scientists to define the correlation/decorrelation length scales for the global network and models. Despite the focus on carbon, required measurements include temperature and salinity (hydrography); nitrogen, phosphorus, silica, and iron (nutrients); and chlorophyll, productivity rates, physiological state, respiration rates, and zooplankton biomass (biology). The sensor suite required by a subset of autonomous underwater vehicles (AUVs) includes temperature, salinity, heat flux, spectral radiance/irradiance, oxygen, nitrate, $p\mathrm{CO}_2$, colored dissolved organic matter/dissolved organic carbon, chlorophyll, primary productivity rates, phytoplankton health (Fv/Fm), zooplankton biomass (acoustics), and export flux (beam-c POC estimates).

Each mooring array would consist of assets 100 km to 200 km apart and would have a moderate vertical profiling capability. Moorings would be complemented by 20 or more autonomous gliders providing synoptic coverage over several months. To define the relative balance of long-term (ENSO/PDO) and high-frequency events (storms), these kick-off experiments should last at least 10 years. Although this example is specific to a geographic region, studies of basin-scale

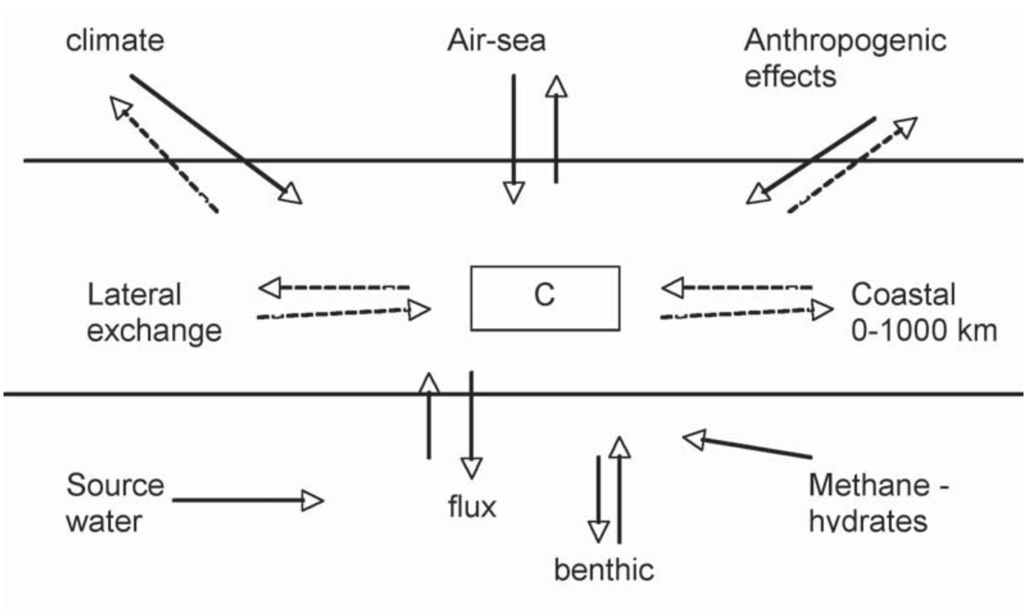


Figure. B-2. Cartoon showing the fluxes that biogeochemical arrays need to resolve. The fluxes and transformations will be resolved with a series of moorings and autonomous underwater vehicles. Figure courtesy of Francisco Chavez.

biogeochemical coupling on ENSO/PDO time scales could be applied to numerous and equally important locations. Experiments such as those proposed above are ambitious, but are the next great challenge for the scientific community. "Whole-ocean" or global-scale problems are inherently 4-D; it is difficult to capture or monitor all appropriate spatial scales (mixing up to basin) without rapidly depleting all assets. Thus, ORION will require significant augmentation of assets above and beyond fixed infrastructure including mobile platforms, modeling, international and collaboration/sharing of resources.

Global Ocean Working Group

- Mark Abbott, Oregon State University
- Rick Baker, Ocean Institute
- Andrew Barnard, WET Labs Inc.
- R. Bigidare, University of Hawaii
- Grace Chang, University of California, Santa Barbara
- Yi Chao, NASA Jet Propulsion Laboratory
- Francisco Chavez, Monterey Bay Aquarium Research Institute
- Lou Codispoti, University of Maryland, Horn Point Laboratories
- Christy Herren, Monterey Bay Aquarium Research Institute
- Mark Moline, California Polytechnic State University
- Rob Pinkel, Scripps Institution of Oceanography
- David Snyder, Gallaudet University

C. Climate, Ocean Circulation, and Mesoscale Mixing

Robert Weller (Moderator), Brian Dushaw (Rapporteur)
Doug Luther (Moderator), Peter Worcester (Rapporteur)

The ocean is an intrinsic component of Earth's climate system and plays a central role in modulating human influences on global climate patterns. Humans may be altering global biogeochemical and climate cycles (carbon, nitrogen, phosphorus, trace metals), thus research efforts need to focus on elemental cycling among land, atmosphere, and ocean. For example, to understand how climate changes may feed back through carbon cycling to alter atmospheric CO_2 concentrations requires the ability to predict how oceanic uptake of anthropogenic carbon will change with changing physical and biogeochemical conditions. Currently, the ocean is estimated to be a sink for anthropogenic carbon, taking up about 30% of the carbon released by human activity. Understanding such global physical and biogeochemical balances requires data that span an extraordinary range of spatial and temporal scales that cannot effectively be observed without a long-term, *in situ* presence such as provided by observatories.

Scientific Priorities

1. Define the relative role of air-sea fluxes, lateral mean advection, and mesoscale eddy mixing on water mass formation in both convective regions (such as the Labrador Sea) and at subductive fronts.
2. Quantify the variability in vertical mixing processes that regulate phytoplankton species composition and biomass, higher-trophic-level composition, and biogeochemical fluxes.
3. Define the respective roles of ventilation and water mass formation versus diapycnal mixing in controlling large-scale stratification.
4. Quantify the sequestration and transfer of carbon from the upper ocean to the deep ocean and seafloor.
5. Understand the climate controls of shallow overturning circulation cells (Subtropical Underwater, Mode Water) at the interannual scale and quantify how these affect phytoplankton dynamics.
6. Determine if eddy formation controls cross-equatorial flow in the tropical Atlantic Ocean.

ORION will provide fixed observational assets in the ocean and overlying atmosphere to quantify spatial (horizontal and vertical) gradients in biogeochemical constituents at appropriate scales. To resolve the wide range of temporal and spatial scales at which biological, chemical, and physical processes act, a distributed, integrated observing network composed of a variety of fixed and mobile platforms will be deployed.

ORION observatories will enable critical sensor development and deployment. Given a new generation of sensors, ORION will show tangible results within five years of the start of experiments; however, the greatest successes will likely be seen through sustained (20 to 30 years) global sampling (covering many different environments, for example, air-sea flux measurements from warm to cold, low wind to high wind, and low wave to high wave). The sustained presence in the ocean will allow scientists to catch events; real-time communications will permit rapid response (with additional resources) when events occur. The observatory's high power and high bandwidth will enable adaptive sampling of episodic events. ORION systems will provide the needed coherent, multi-scale networks in extreme environments at polar latitudes. ORION systems will enable global acoustic thermometry, navigation, communications on all scales, mid-water platform nodes (with communication and power to bottom nodes), and climate-quality calibration, and will provide a large base of core instrumentation.

Example ORION Experiments

What are the climate controls on water mass formation, air-sea fluxes, and vertical mixing? What are the associated interactions with ecosystem structure and biogeochemical processes?

Developing a robust global biogeochemical budget requires a thorough understanding of the temporal evolution of water masses and the nature of their source waters. For example, the biogeochemistry associated with North Atlantic Deep Water (NADW) as it is formed represents a significant basin-wide transport mechanism for heat, salt, and elements (carbon, nitrogen, iron). The water mass is progressively modified as organic material sinks to the benthos or is remineralized during its southerly transport in the Atlantic Ocean. To study these transformation processes, a combination of Eulerian and Lagrangian platforms should be combined to study water-mass formation, transport, and evolution. Eulerian platforms placed in strategic geographic locations would provide the sustained high-frequency measurements capable of quantifying seasonal water column stability and overturning. High-frequency data would allow scientists to assess the potential importance of storms, which currently is not sampled by traditional expeditionary mode research strategies. The spatial picture, around and between the Eulerian points, would be sampled using long-lived Lagrangian platforms. The spatial data would anchor studies focused on the transformation of the water mass and material within it. Such a network, if deployed for sustained periods, would provide the data to enable the development, parameterization, and validation of global biogeochemical models. Eulerian points could also be outfitted with sediment traps to provide estimates of the export flux providing the basis for building robust biogeochemical budgets for key ocean water masses. The OOI investment for a fixed number of Eulerian assets would complement assets planned or already deployed by other federal agencies and international partners.

The working group identified several high-priority regions to study. The working group suggests initially locating at least one full-capability moored buoy observatory in the middle of each target region: the Labrador/Irminger Seas (upper North Atlantic Deep Water [NADW] formation), the Southeast Pacific (Antarctic Intermediate Water [AAIW] formation), and Weddell Sea (Antarctic Bottom Water formation [AABW]). At some sites, these moored buoys might be powered with seafloor cables; however, this possibility depends on the proximity to shore. The Labrador Sea might be an ideal candidate for cable deployment. At each moored buoy observatory site, autonomous gliders would provide the spatial information to complement the fixed times-series data.

The first study area should be a heavily clouded region such as the Labrador/Irminger Seas. The heavy cloud cover constrains the utility of remote-sensing approaches, so these critical ocean areas are chronically undersampled. Initial goals would be to characterize the spring bloom (and the resulting export flux) and the springtime stratification and the subsequent autumn-winter convective overturn. In five years, studies of the southwest of South America in AAIW source region, which is a major region carbon sequestration in the global oceans, should be initiated. After five years, ORION should consider experiments in harsher environments.

The proposed system, given existing off-the-shelf technology, could provide data on the physics (temperature, salinity, currents), chemistry (pCO_2, O_2, TIC, pH, nutrients, dissolved organic matter), and biology (particle organic load, phytoplankton concentration). These sites should be populated with constellations of tomographic moorings and long-range

ADCPs. The array's backbone should include operational spectral optical sensors that describe the phytoplankton and colored dissolved organic matter. Higher trophic levels and marine snow can be measured using a combination of optical imaging and acoustical methods. The observatory should have a surface expression to allow sensors to provide high-accuracy air-sea flux measurements that will be combined with satellite observations. Chemical measurements should be made using a combination of "wet" chemistry and optical-based sensors.

What are the dynamics, energetics, impact on circulation (particularly abyssal), and global importance of topography-catalyzed mixing processes?

The interaction between climate and seafloor topography on mesoscale and basin-scale circulation and mixing processes remains a difficult problem to assess using traditional sampling strategies. Unfortunately, until our understanding improves, our ability to verify existing numerical models, which ultimately would allow for a robust global extrapolation, is very limited. Given these needs, an ambitious observational program needs to be initiated over a variety of topographic environments (e.g., continental slopes with and without corrugations, ridge crests, ridge flank valleys, fracture zone scarps, and abyssal hills). These observational efforts could be easily coupled to a wide range of complementary efforts such as bottom boundary layer dynamics.

High-resolution measurements of currents and stratification, spanning the seafloor to the thermocline, are required. Seafloor to thermocline measurements of micro-scale temperature variations and current shear are required to directly estimate turbulence amplitudes. This will require small arrays of long-range ADCPs that could be powered by either cables or moorings. Moored profilers are a key to this experiment (e.g., McLane moored profilers) with the sensors powered and controlled by the observatory backbone (cables or moorings). Gliders are required to provide the horizontal and vertical definition of mixed waters as they advect from the boundary. Acoustic tomography can complement the gliders in providing the larger-scale context. A cabled observatory along the Juan de Fuca Ridge would fulfill many of the topographic needs for this experiment.

We propose a kick-off experiment with a small array of fixed instruments on the continental slope near Washington, Oregon, or northern California. This array could be augmented on an annual basis. At four-year intervals it would be important to establish additional arrays in different topographic settings or current regimes (e.g., near the California Current).

What is the impact of episodic (high-frequency) phenomena on longer-time-scale physical, biological, and chemical variability?

The relative importance of episodic events remains a central question to all disciplines of oceanography. For example, the importance of episodic events is central to questions such as: What is the effect of the variability of storm strengths and storm tracks on thermocline ventilation, nutrient injection to the photic zone, phytoplankton blooms, and biogeochemical fluxes? What is the relationship between climate and shorter-time-scale phenomena such as mesoscale eddies, hydraulic flows, internal waves, squirts and jets, and intra-seasonal oscillations? To answer these questions requires multidisciplinary experiments to capture the surface-to-bottom effects of storms over a long enough time period to determine how one event differs from another, and to determine the relative influences of pre-storm conditions and interannual variability. At a minimum, experiments in the sub-arctic, subtropical, and tropical regions are recommended. Priority measurements include surface fluxes of momentum, heat, gas, and light. Within the mixed layer, priority measurements include temperature, salinity, oxygen, carbon dioxide, nutrients, *in situ* phytoplankton concentration, and, ideally, composition and turbulence. Below the mixed layer, priority measurements include temperature, salinity, particulate organic carbon, dissolved organic carbon, and current velocity. Sensor development is required to make all of these measurements over long, continuous time periods. It is critical that horizontal variability be characterized through floats, gliders, and additional moorings with acoustic tomography.

An initial kick-off experiment is proposed for the North Pacific sub-arctic gyre using the North Pacific regional cabled observatory. Within three to five years, an array capable of tracking hurricanes and their associated effects in the tropical and temperate Atlantic will be a high-priority focus. After five years, experiments should be conducted in the Southern Ocean.

How does the inventory and transport of physical, biological, and chemical properties vary on climate-relevant time scales at key locations?

Despite much progress, our understanding of the variability in the transport of heat, salt, carbon, nutrients, and biological species related to modes of climate variability (e.g., ENSO, NAO, PDO, SAM, MOC) remains limited. This limited understanding undermines our ability to interpret observed trends in the ocean, the potential ecosystem responses, and corresponding feedbacks on the climate system. These issues are particularly important in climate-sensitive regions, such as those in polar latitudes. Given the prominence of these issues to policy-makers and their importance to future human societies, climate research efforts are a high priority.

Initial experimental focus should be determining the physical forcing of ocean ecosystems and associated biological carbon flux. Key experimental locations should be areas of mass-freshwater-heat transport, such as the Indonesian throughflow, the Arctic and Greenland outflows, the Antarctic Circumpolar Current in the Drake Passage, and strong boundary currents. Efforts should also be in areas of strong hydraulic flow, such as the abyssal circulation at sills found off Greenland and Iceland. Other interesting areas for experiments are those associated with high fluxes due to eddies. Good candidate locations might include the Brazilian and Agulhas Current retroflections. Priority measurements include surface fluxes of momentum, heat, gas, and light. Within the mixed layer, priority measurements include temperature, salinity, oxygen, carbon dioxide, nutrients, *in situ* phytoplankton concentration, and, ideally composition and turbulence. Below the mixed layer, priority measurements include temperature, salinity, particulate organic carbon, dissolved organic carbon, and current velocity. Sensor development is required to make all of these measurements over long, continuous time periods. It is critical that horizontal variability be characterized through additional moorings, floats, and gliders.

Initial experiments could be conducted in the Arabian Sea, leveraging experience gained during the JGOFs effort. Within three to five years, experiments should be carried out using a mesoscale-resolving observing array in the West Wind Drift area of the United States as the cabled network is deployed. Within three years, experiments could be initiated in biogeochemical provinces such as the North Pacific. After five years, experiments looking at the Antarctic Counter Current transport, Indonesia throughflows, Arctic outflows, and the Drake passage would all be great candidates for a full experiment.

Synergistic Needs Beyond OOI Infrastructure and Plans

Success for ORION will require extended spatial coverage beyond point moorings, using, for example, gliders and profiler arrays around observatories; roving AUVs navigated acoustically to docking stations; bottom roving, eco-sampling crawlers (like Mars rover); freely drifting RAFOS floats enabled by acoustic signals; radar and sonar; and remote, self-contained instruments communicating acoustically with the observatory. To deploy this wide variety of platforms will require allocation of spectrum for acoustics and ship time for sampling at and around point moorings. Success will require coordination with national and international science planning and with national and international operations, and implementation and cross-calibration across national and international observing programs.

Needed Technology Developments

ORION will require technology development. Specific needs include biological and chemical sensors; advanced moored profilers with improved power, communication, and payload; microstructure sensors for moored profilers; improved optical sensors-biophysical feedbacks; and acoustical and molecular imaging. Additionally, development of easy onboard standardization/calibration; docking stations for roving AUVs and bottom-roving, eco-sampling crawlers (like MARS rover); and long-range (1000 m and more), bottom-mounted ADCPs are required. Development of better fouling mitigation strategies for instruments, better near-surface current meters, low-frequency acoustic source arrays, and improved air-sea flux sensors (turbulent and mean, measuring and dealing with platform motion, stabilization/gimbaling) is needed. Finally, improved ship sensors for calibration of moored sensors on recovery/deployment cruises, bottom following floats, and biogeochemical floats deserve focused development efforts.

Management, Data Policy, and Archive Needs

ORION's success will depend on its data delivery and archival systems. It is recommended that ORION coordinate science planning internationally and with the Integrated Ocean Observing System (IOOS), and coordinate data management internationally and with IOOS. It is recommended that data management and communication mesh ORION with the IOOS Data Management and Communications (DMAC) system, which will require coordinated IOOS management with ORION operations. ORION should follow international requirements for DMAC hardware, systems, and servicing (all bits must work together).

Climate, Ocean Circulation, and Mesoscale Mixing Working Group

- Art Baggeroer, Massachusetts Institute of Technology
- Jorge Corredor, University of Puerto Rico
- Brian Dushaw, University of Washington
- Charles Eriksen, University of Washington
- John Garrett, NEPTUNE Canada
- David Halpern, Office of Science and Technology Policy
- Peggy Hamner, University of California, Los Angeles
- Bruce Howe, University of Washington
- Mike Johnson, NOAA Office of Global Programs
- Yoshifumi Kuroda, JAMSTEC
- Richard Lampitt, Southampton Oceanography Centre
- Doug Luther, University of Hawaii
- Roger Lukas, University of Hawaii
- Peter Mikhalevsky, SAIC
- Jerry Mullison, RD Instruments
- Vadlamani Murty, National Institute of Oceanography
- Mary Jane Perry, University of Maine
- Uwe Send, IfM Kiel
- Rochelle Slutskin, Anne Arundel County Public Schools
- Alexander Soloviev, NOVA Southeastern University
- Michael Spranger, University of Florida
- Ted Strub, Oregon State University
- Andreas Thurnherr, Lamont-Doherty Earth Observatory
- Sara Tweedie, Tweedie & Associates
- Robert Weller, Woods Hole Oceanographic Institution
- Robin Williams, University of Puerto Rico-Mayaguez
- Peter Worcester, Scripps Institution of Oceanography

Box 4. Education Scenario: "Adopt a Float"

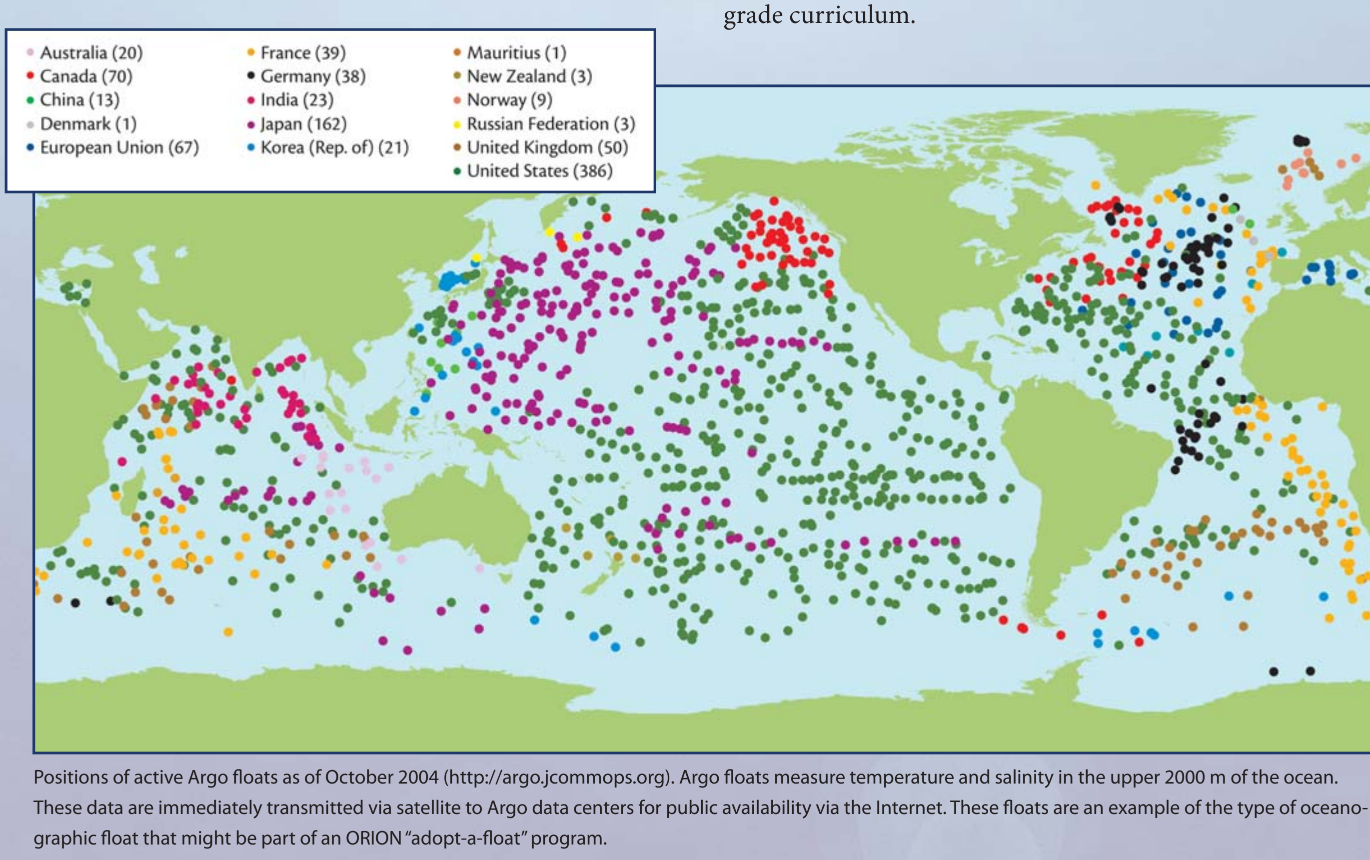
Contributed by Veronique Robigou, University of Washington, and Tracy Kirby, Ocean Institute.

At the start of the school year, students in eleventh and twelve grades access a network of floats deployed throughout the world's oceans. Each float collects information on its location, seawater salinity, and temperature, and instrument depth (see figure). In addition, the floats are equipped with hydrophones that can register earthquakes. Classes select a float from a location map on the ORION web site. The selected float becomes the class "adopted" float for the school year. Each float can be adopted by several classes. This activity will provide students with opportunities to compare observations made at the same time or on the same day with other classes in the country or abroad. It could also provide opportunities to multiply the number of observations made on one float if each class takes a turn within a week to make their observations. This activity models the collaborative approach to scientific research inherent to inquiry-based science.

Through ORION web-based resources, students will be able to view "their" float as often as feasible within the constraints of the curriculum. With the teacher's guidance, students will plot float data using graphing tools developed by ORION scientists and educators. Students will become familiar with these tools and practice rigorous scientific protocols developed by scientists for data analysis. Access to scientists supporting this activity will be available through an "Ask an ORION Scientist" and a teacher-student/scientist chat room.

Classes can also decide to link more directly with an interested research scientist involved in a particular project. In addition to working on data from its float, each student group, or "mission" team, will follow one particular scientist and his/her research throughout the year. Communication between the "team" and researcher can be done over the web and, in some cases, through videoconferencing.

The goal of this project is to encourage teachers to address scientific concepts by using real ORION data and inspire students to practice required math and science skills through an oceanographic scenario. The project can culminate in a "citizen project" where students and teachers contribute to an ongoing research project without compromising the necessary grade curriculum.



Positions of active Argo floats as of October 2004 (http://argo.jcommops.org). Argo floats measure temperature and salinity in the upper 2000 m of the ocean. These data are immediately transmitted via satellite to Argo data centers for public availability via the Internet. These floats are an example of the type of oceanographic float that might be part of an ORION "adopt-a-float" program.

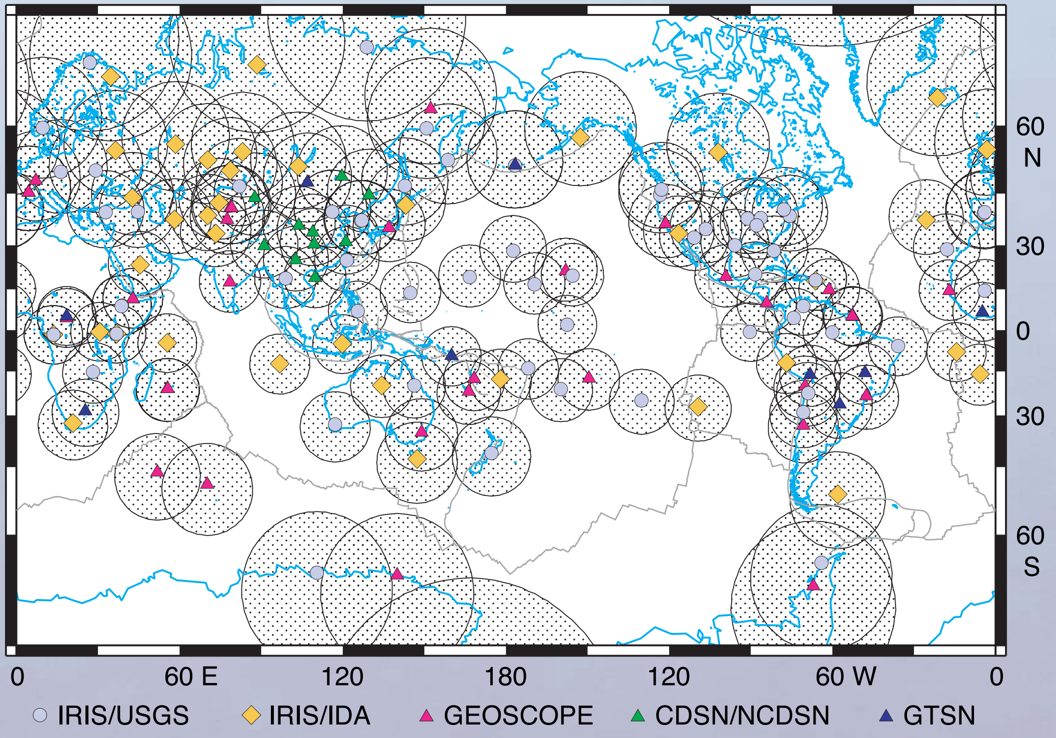
Box 5. A Global Observatory Network of Moorings for Interdisciplinary Science

Contributed by Bob Weller, Woods Hole Oceanographic Institution, John Orcutt, Scripps Institution of Oceanography, and Uwe Send, University of Kiel (Germany)

With growing awareness of the role that the ocean plays in weather, climate, and human health and well-being, ocean time-series observatories have been identified as a critical component of the Global Ocean Observing System (GOOS). At the same time, Earth scientists have long recognized the need for a truly global distribution of fixed geophysical stations to address questions about Earth's internal structure and the dynamics of convection within the core and mantle. For Earth-structure studies, the paucity of measurements in the Southern Ocean is particularly acute because of the scarcity of oceanic islands, as can be seen in the figure below (also see Earth Structure working group report).

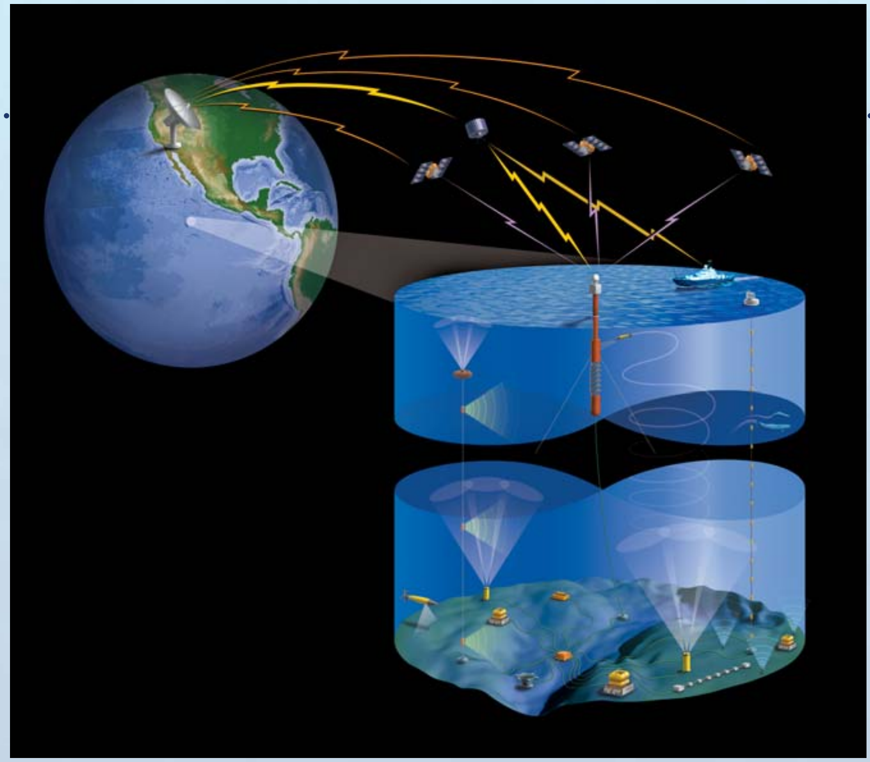
With new mooring and instrumentation technology, it is now possible to effectively deploy and maintain unmanned observatories that will autonomously carry out diverse measurements over extended periods of time while providing much of the data via satellite in near real time (figure, opposite page, top). Moorings can place instruments at the sea surface, through the water column, and on the seafloor. These attributes make moorings a key resource for observing cause and effect, such as between surface heat loss and sinking of surface water, and interrelationships between diverse fields, such as between upper ocean mixing and phytoplankton blooms. They are also uniquely suited for sampling critical or adverse regions and periods (e.g., straits, boundary currents, boundary layers, ice-covered regions, storm seasons).

Key locations, such as where water masses form, where carbon dioxide is exchanged with the atmosphere, where the ocean transports heat in strong boundary currents, where populations are changing, and where no seismometers exist on the seafloor, must be instrumented (figure, bottom). Change and variability in the Earth system can operate over

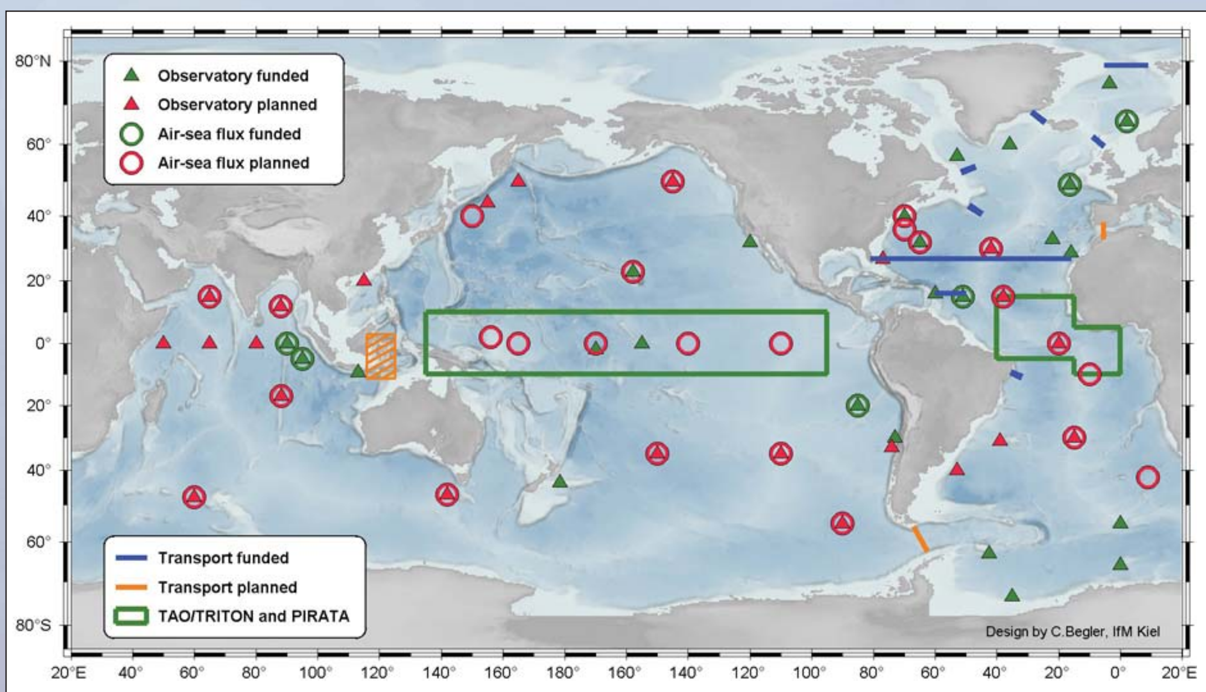


Global Seismic Network stations from a variety of systems located on continents and Islands are shown, with each surrounded by a 10° radius circle. A substantial number of new stations (20-25) is required to achieve a minimal global coverage for studies of Earth's deep interior.

large spatial scales; variability at one location can drive variability at sites far away. El Niño and its remote influences are a good example of this. Thus, sites for time-series observatories have been identified across the world's oceans. The plan is for an internationally coordinated global array (OceanSITES) to observe in diverse regions, understand and contrast the processes at work in those regions, and to identify patterns.



Schematic of a moored buoy, linked to shore via satellite, and able to support measurements of air-sea fluxes; physical , biological, and chemical water properties; and geophysical observations on or below the seafloor. Figure courtesy of John Orcutt, Scripps Institution of Oceanography.



Potential sites located at the intersection of regions of interest for multiple disciplines, with priority given to sites where infrastructure is shared among multiple disciplines (e.g., air-sea interaction, physical oceanography, biogeochemistry, ecosystem dynamics, global seismology, geomagnetism, and geodesy). Sites were identified by OceanSITES (locations are from www.OceanSITES.org). Mobile platforms and acoustics will be needed to fill in data gaps between moored sites.

D. Earth Structure

Guust Nolet (Moderator), John A. Orcutt (Rapporteur), John Collins (Contributor)

Seismology is the premier tool for understanding Earth's interior, but our ability to map global structure is constrained by the spatial distribution of earthquake sources and seismic stations. Seismic body and surface waves are sensitive to structure along localized paths determined by earthquake source and receiver locations; structures away from these paths are not sampled and cannot be well defined. Earthquake sources are largely confined to plate boundaries, primarily subduction zones, and in a rough sense, absenting the creation of a new plate boundary, the pattern of source locations is fixed. Source-receiver paths are then a function of receiver locations (Figure D-1). With few exceptions, all permanent seismic stations are located on continents or oceanic islands. Future seismograms recorded at existing or new land-based stations will represent additional and better sampling of the same paths, or new sampling of structure close to these paths. Given that ~75% of Earth's surface is covered by water, and that oceanic islands are scarcely and irregularly distributed, it is clear that vast portions of Earth's interior cannot be sampled using land stations. The paucity of measurements in the Southern Ocean is particularly acute because of the scarcity of oceanic islands. The obvious solution to this sampling problem is to deploy seismic stations on the ocean floor.

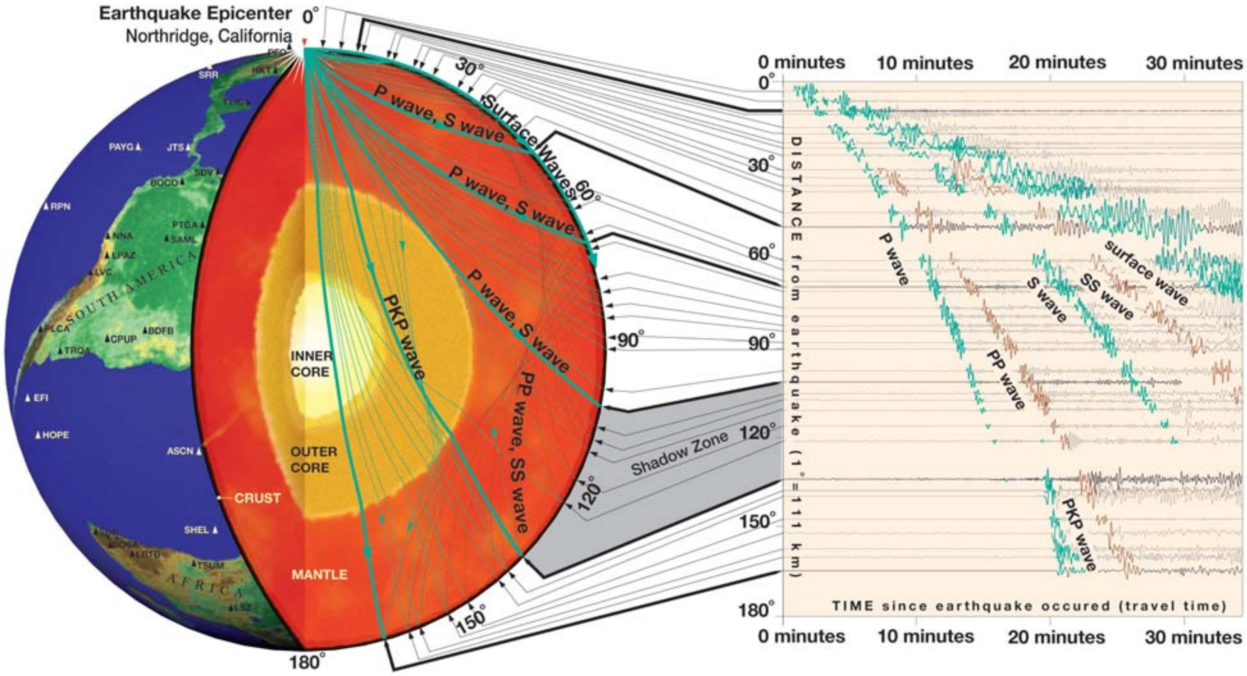
Every seismogram recorded on the seafloor represents a sampling of a hitherto unexplored portion of Earth's interior. Seafloor stations will allow better locations of moderate-sized oceanic events, making these events useful for structural studies. The current generation of whole-Earth tomograms represents ~40 years of data. For ocean-floor seismic data to be of use, seafloor stations will have to be operated for at least 10 years, preferably longer. The seismological community has called for ~20 seafloor stations to be broadly distributed throughout the oceans (precise location is flexible) with priority being given to stations in the Southern Ocean (e.g., Purdy and Dziewonski, 1988; Orcutt and Purdy, 1995).

Inadequate spatial sampling is also a severe obstacle to understanding the geomagnetic field and to imaging electrical conductivity variations in the mantle. Adequate magnetic field models will require a global geomagnetic observatory spacing of no more than 2,000 km—including eight seafloor

Scientific Priorities

1. Document the structure of Earth's interior, and determine its composition.
2. Determine the scales of convection within the solid Earth.
3. Determine the important mechanisms of heat transfer from the core to Earth's surface, and how they control plate deformation and motion.

Figure D-1: Seismic waves generated by earthquakes, such at the 1994 Northridge CA earthquake, propagate through Earth's interior and, when recorded on seismographs at different distances from the event, can be used to infer the internal Earth structure. Figure from www.iris.edu/edu/onepagers.htm, "Exploring the Earth Using Seismology."



sites. 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. In recent years, electromagnetic induction measurements have been used to generate 3-D electrical conductivity models of the upper- and mid-mantle. Conductivity is sensitive to variations in mantle temperature and the presence of partial melt, water, volatiles, and hydrous mineral phases. Global mapping of Earth's conductivity structure will require ~20 seafloor sites in addition to those at island stations.

The OOI infrastructure can provide a distributed network of instruments (e.g., seismic, electromagnetic, magnetic) in regions far from land that will fill critical data gaps that currently render incomplete tomographic solutions for the mantle, and incomplete data about convection within the core and mantle.

Measurements required at fixed stations developed by ORION for understanding deep Earth structure include broadband seismology, magnetic (B) and electric (E) vector fields, and geodesy (bottom pressure, absolute gravity, GPS/acoustic absolute position). Many of these fixed stations will be located in areas of the ocean that are of great interest for ocean studies of climate (see box on p. 26). For example, full-capability moored buoy observatories are desired to study carbon production and biogeochemical processes within water-mass source regions such as in the Southeast Pacific (Antarctic Intermediate Water) or the Weddell Sea (Antarctic Bottom Water Formation), and elsewhere in the Southern Ocean to capture surface-to-bottom effects of storms. Thus, many of these stations will be able to fulfill a dual role of providing critical information about Earth structure, and about ocean and atmospheric circulation (see Climate working group report). The OOI infrastructure will provide an unprecedented opportunity to eliminate a sampling bias that has existed for decades, and that will endure as long as stations are limited to continents and islands, sampling depends upon individual proposals, and siting relies upon mission agency support.

Example ORION Experiments

With a truly global distribution of instruments, it would be possible to infer Earth's detailed deep structure through seismic tomography. For example, due to the absence of stations in the ocean, there is poor resolution of mantle structure in the southern versus northern hemisphere (Figure D-2). Addition of even a few stations could greatly improve our insights into mantle processes, and allow us to address a number of unanswered questions such as those described below.

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

One of the great unanswered questions regarding mantle structure and dynamics is the pattern of convection in the mantle, and the origin and scales of mantle heterogeneity.

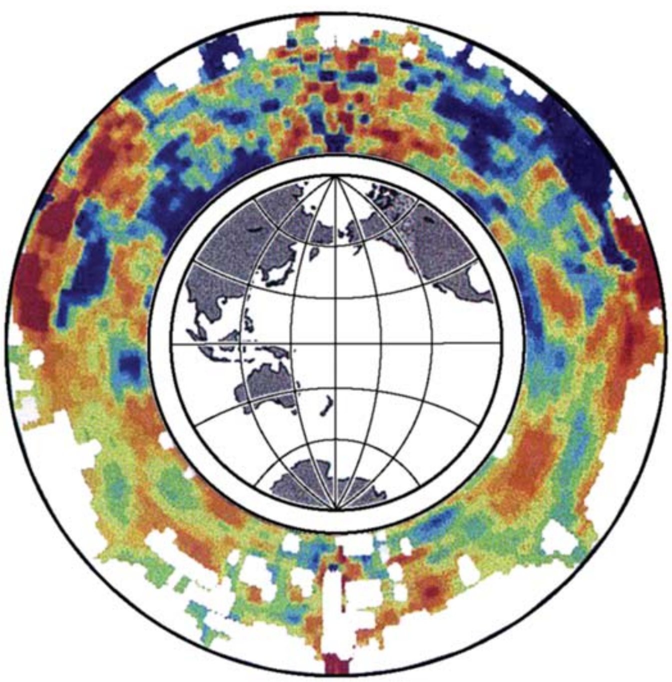


Figure D-2. Example of poor resolution of mantle structure in the southern hemisphere because of the lack of seismic stations in the ocean. A polar cross section through the model of van der Hilst et al. (1997) is shown, with undersampled regions in white. Figure is from Boschi and Dziewonski (1999).

The chemical heterogeneity revealed by isotope and trace-element studies seems to require that the mantle is either stratified into isolated layers, or that mantle convection does not efficiently mix chemical heterogeneities, or some combination of these processes. 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 has shown that some subducting slabs extend well into the lower mantle (Figure D-3A and B), casting doubt on a layered convective model. How far these slabs penetrate into the lower mantle, and the rheology of lithospheric material once in the lower mantle, are matters of active debate. In some cases slabs appear to lay out at the 660 km discontinuity. In other cases they appear to sink deep into the lower mantle, though they often "fade away" well above the core-mantle boundary. However, it is unclear whether this is "real," and slabs do not extend below this depth, or whether this is an artifact of poor seismic resolution in the lowermost mantle. Our ability to resolve this kind of heterogeneity, especially in the lower mantle, is significantly limited by the lack of seismic observations in the oceans.

Another major controversy in mantle dynamics centers around the origin of volcanic centers such as Hawaii or Iceland. Since Jason Morgan first proposed the "mantle plume" hypothesis in 1972, many researchers have argued that these "hotspots" are caused by rising plumes of hot material originating near Earth's core. Others have maintained that hotspots originate in the upper mantle and do not have a deep origin. Still others have argued that while some mantle plumes rise from the core-mantle boundary (CMB), others originate in the mid-mantle or at the base of the upper mantle. The abundance of hotspots in the Pacific Ocean (Hawaii, Galapagos, Marquesas, Tahiti, Samoa) make this an ideal region to test the mantle plume hypothesis; however, large regions of the South Pacific are devoid of seismic stations because of the absence of islands. Even a small number of seafloor seismic stations (4 to 6) located in regions without islands (e.g., between Chile and New Zealand) would significantly improve our ability to image plume conduits in the mid- and lower mantle, and subducting slabs, thus allowing us to test differing plume and slab subduction hypotheses.

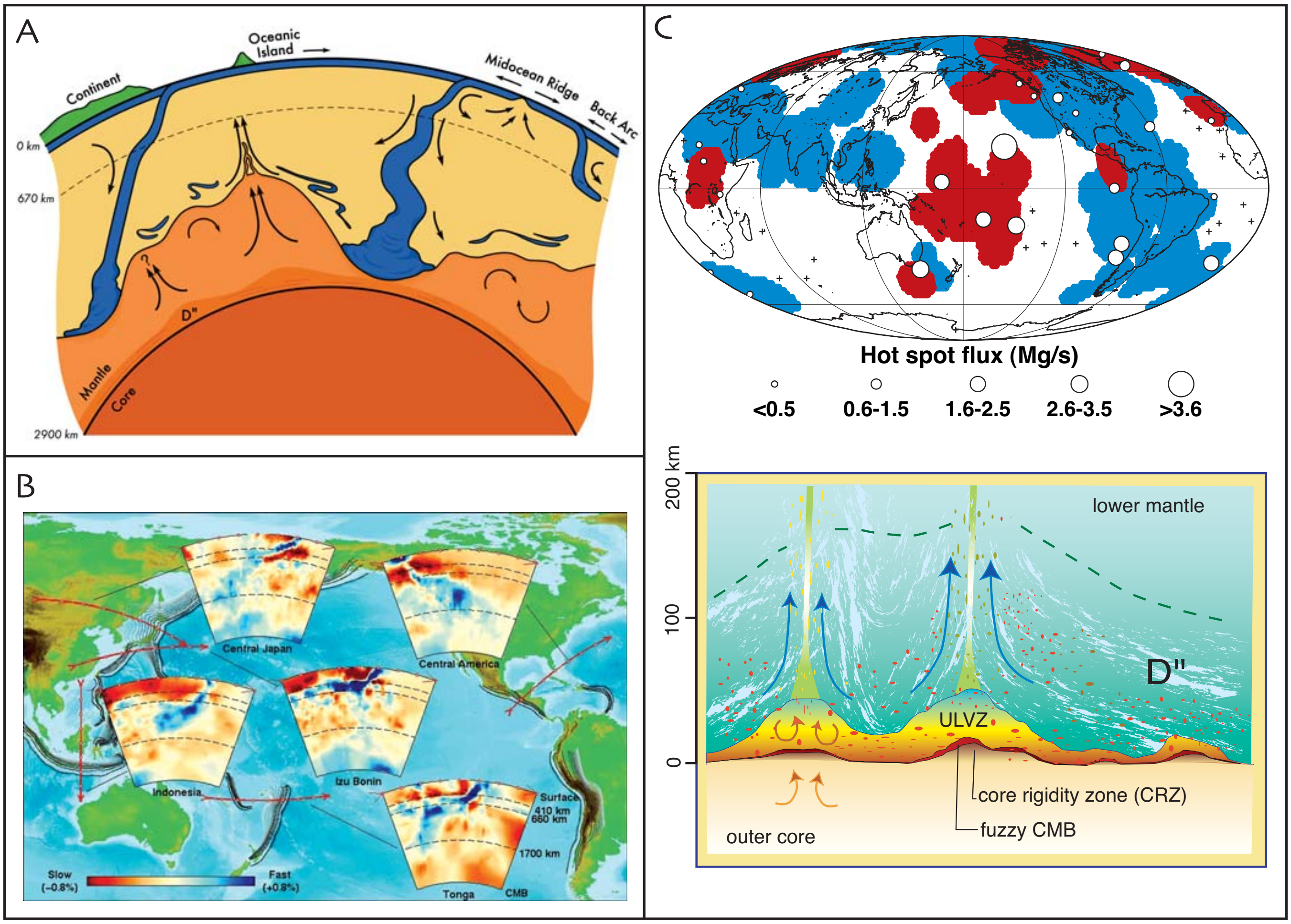


Figure D-3: A. Schematic diagram of possible mantle structure (Figure from Kellogg et al., 1999, reprinted with permission, AAAS). B. Seismic tomographic images showing subducting slabs, indicated by blue colors or fast velocities; dashed lines are drawn at depths of 410, 660, and 1700 km, with the base at the crust –mantle boundary (CMB) (Figure from Albarede and van der Hilst, 2002). C. ULVZs (shown in red) appear to correlate with the superplume beneath the south Pacific, and they don't seem to occur (blue) where subduction of the ocean lithosphere is occurring (from Garnero et al., 1998 and Garnero, 2000).

An exciting, though still very experimental, option is to equip autonomous floats with hydrophones and record teleseismic waves under water with an ever-changing array. Floats are already extensively used by the oceanographic community, but their possible use for seismology has only very recently become clear (Figure D-4).

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

The structure of Earth's core and CMB is a "last frontier" 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 in the dynamo, which 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, so-called Ultra-Low Velocity Zones (ULVZ), but it is not clear what these features are. Are they partially molten mantle material, some kind of core-mantle reaction zone, exotic layering, or sedimentation on the underside of the CMB? One clue about their origin comes from where they are found. The ULVZs (red areas in Figure D-3C) appear to correlate with the superplume beneath the South Pacific, and they

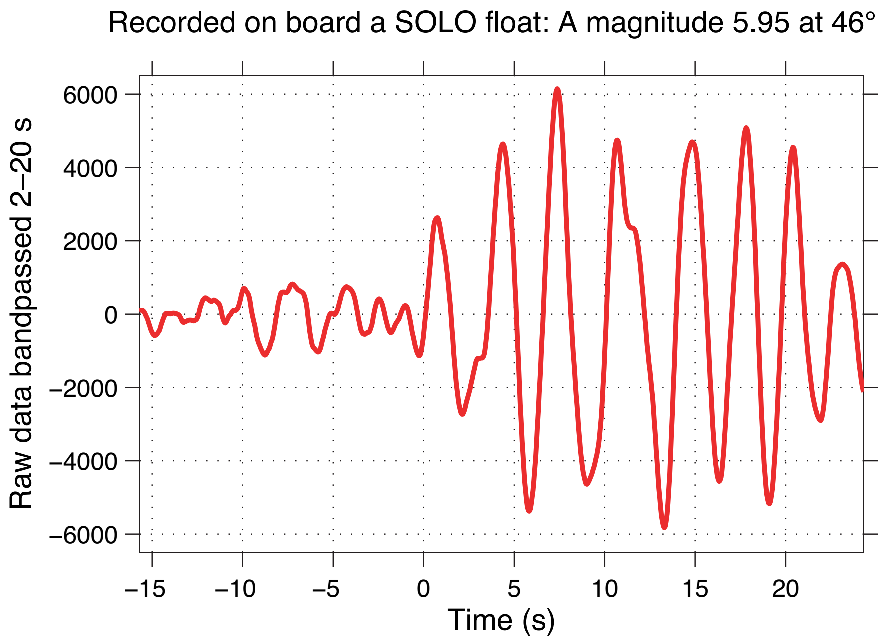


Figure D-4. An experimental MERMAID float equipped with a hydrophone was deployed by a joint team from Scripps Institution of Oceanography and Princeton University. Drifting for about 30 hours at a depth of 700 m, it recorded this onset of a P wave from a magnitude 6.0 earthquake at a distance of 46 degrees. Figure courtesy Frederik J. Simons, University College London.

don't seem to occur where subduction of the oceanic lithosphere is occurring (blue areas in Figure D-3C). However, sampling of CMB properties is incomplete, largely because of a lack of stations in the oceans, and as a result, these ideas remain speculative. Even a few additional stations, for example, in the southern Pacific and Indian Oceans, would help to test these hypotheses about the nature of the ULVZs.

Data from stations in the Atlantic Ocean could allow other hypotheses to be tested, particularly hypotheses about the outer core. The Tonga trench and other subduction zones of the western Pacific are locations of the most abundant large and deep earthquakes, and consequently are near ideal sources for structural investigations. However, compressional-wave phases from these events that sample Earth's core (PKP) and the outermost portion of the inner core "emerge" in the equatorial Atlantic region (Figure D-5). Even a small number of seafloor seismic stations (3 to 4) in the central Atlantic would significantly improve our ability to resolve core structure.

Issues to Resolve

Completion of a truly global geophysical network will require site surveys, installing equipment in areas where sea states are high, and stable instruments. Seismic measurements in the ocean are best done using instruments placed in boreholes drilled by the Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP). At a minimum, site surveys are required to determine sediment thickness at the proposed site. Other geophysical measurements do not require or use boreholes for instrument placement, in which case the surveys for drilling provide an adequate background for installation.

In terms of instrument readiness, borehole seismometers have been developed and tested for long-term measurements (e.g., Collins et al., 2001; Stephen et al., 2003). Electromagnetic measurements over extended periods are common in the ocean and the electrometers are straightforward

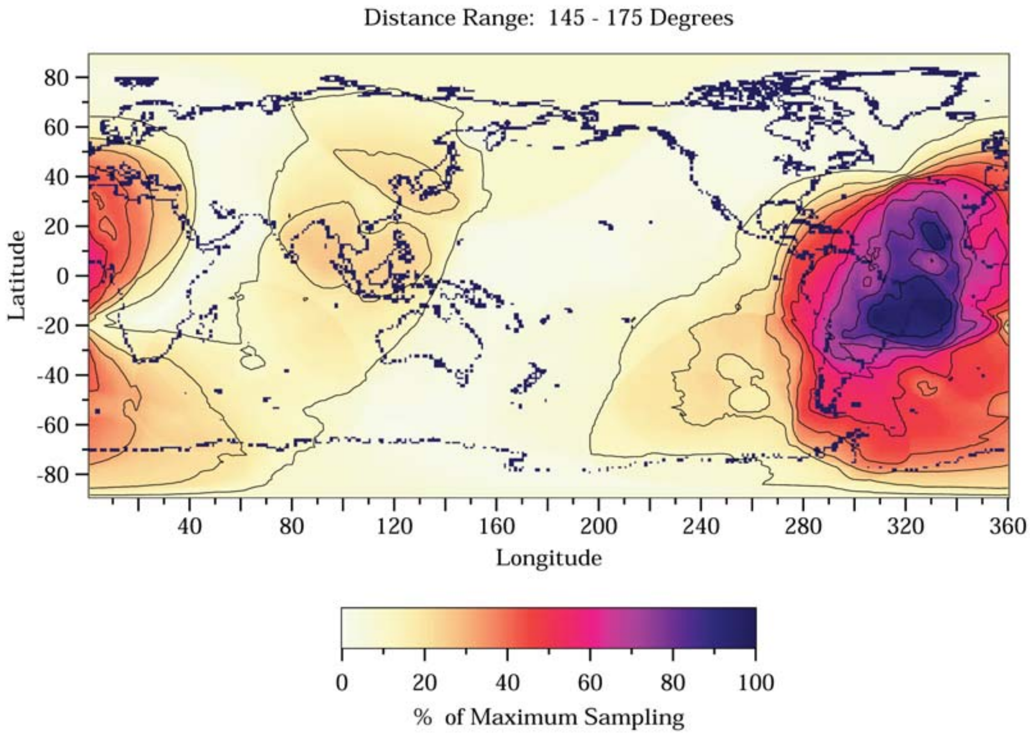


Figure D-5. The central Atlantic is the optimum location to record compressional-wave phases that interact with Earth's outer core. These phases are observed at epicentral distances of 145° to 170° (see Figure D-1). The contours show the percentage of global seismicity, as a percentage of the maximum sampling, for this distance range. The large percentages for the central Atlantic reflect the fact that the subduction zones of the western Pacific are locations of the most abundant large and deep earthquakes. The data for this figure are from a 20-year catalog of events with body wave magnitude greater than or equal to 5.7. Figure from Wysession (1996).

to install (e.g., Key and Constable, 2002). The orientation of seafloor geomagnetic stations presents an interesting problem, but is not considered to be insurmountable (e.g., Green and Chave, 1999).

Outreach

The theme of "Conquer the Elements in the Southern Ocean!" is a potentially popular idea for attracting the public's attention to the major challenge of instrumenting and measuring the Southern Ocean.

Informal education: The Ocean Mantle Dynamics "flexible array" could provide special opportunities:

- Multiple deployment/recovery opportunities to provide teleconferencing in real-time with schools, museums, aquaria, and educational institutions
- Multiple deployment and recovery opportunities to expand the concept of "teacher-at-sea" experiences

Formal education: The deployment of permanent seafloor observatories at the scale of the planet was attractive from several angles:

- Interdisciplinary aspect of arrays will be interesting within the context of inquiry in science education
- Possibility of students and teachers plugging into a seafloor node to retrieve data, follow experiments, and compete for new instruments using the NASA model
- Simulation of solid Earth observations using physical models in the classroom (e.g., transducers/receivers for high school students and simple computer models)

There is the potential for a classroom "adopt a float" program (see box on p. 25) given that there will be fleets of floats at sea with hydrophones for detecting earthquakes and measuring arrival times. Trained teachers might contribute to system quality control and the general public could follow the evolution over time of the system through the WWW and the press.

The Key to Success: National and International Support

A decadal program to install 30 moorings around the planet with an emphasis on the southern hemisphere is costly but possible using a combination of resources. Three installations each year is realistic beginning with the start of OOI funding in 2006 (Detrick et al., 2000). The installation of 15 stations during the course of the OOI, assuming equal numbers of deep and shallow water moorings, is $61.8M, with the full suite of seismic, geodetic, EM, magnetometer, and acoustic thermometry hardware costing an additional $10.5M.
The international geophysical communities and the United States have been pursuing ocean observatories for years (e.g., Purdy and Dziewonski, 1988; Dziewonski and Lancelot, 1995; Orcutt and Purdy, 1995; DEOS Global Working Group, 1999; International Working Group Support Office, 2001; Orcutt et al., 2003). The Ocean Seismic Network (OSN) and OceanSITES have developed jointly prioritized locations for observatories. The International Ocean Network (ION), in which the United States is a partner, is pursuing the installation of geophysical observatories globally. The most recent symposium report was given in Japan in January 2001 (Romanowicz and Suyehiro, 2001). Japan has installed a number of seismic and geodetic stations as part of this program.

Earth Structure Working Group

- Chris Barnes, University of Victoria
- John Collins, Woods Hole Oceanographic Institution
- Fred Duennebier, University of Hawaii
- Nigel Edwards, University of Toronto
- Junzo Kasahara, University of Tokyo
- Tracy Kirby, Ocean Institute
- Gabi Laske, Scripps Institution of Oceanography
- Hitoshi Mikada, Japan Marine Science and Technology Center (JAMSTEC)
- Guust Nolet, Princeton University
- John Orcutt, Scripps Institution of Oceanography
- Michael Purdy, Lamont-Doherty Earth Observatory
- Veronique Robigou, University of Washington
- Adam Schultz, Oregon State University
- Frederik Simons, Princeton University
- Ralph Stephen, Woods Hole Oceanographic Institution
- Pascal Tarits, Université de Bretagne Occidentale/ Institut Universitaire Européen de la Mer
- Spahr Webb, Lamont-Doherty Earth Observatory

E. Fluid-Rock Interaction and Its Influence on Life

William Wilcock (Moderator), Lauren Mullineaux (Rapporteur)

The oceanic crust and sediment blanket are saturated with fluid whose chemistry varies depending on which path it takes through the seafloor (Figure E-1). Pore fluids and seawater can interact with hot rocks in the vicinity of mid-ocean ridges and back arc spreading centers, resulting in the formation of high-temperature fluids that are expelled rapidly and dramatically from black and white smoker chimneys. Alternatively, they can interact with the sediments and cooler warm oceanic crust on the flanks of ridges, or with sediments at very low temperatures along continental margins, and incorporate crust- and sediment-derived fluids and gases. Though pathways may be different, the chemistry of the rocks and sediment through which the fluids have passed is changed, as is the surrounding seawater. These changes affect the composition of the oceans and oceanic crust, and can influence biological communities. Fluids can also affect the mechanical stability of sediments.

For example, we currently do not know the relative importance of water, gas, and earthquakes in triggering giant slumps and slope failures along ocean margins. What is known is that, within fluid-dominated seafloor environments, geological, chemical, and biological processes are linked. Transient events are common yet difficult to observe and sample using traditional, ship-based methods. Evidence of the importance of transient events has been documented in many different environments, including mid-ocean ridges, passive and active ocean margins, and in the fore-arc and back-arc regions of subduction zones. Adequate study of these events requires that environments be observed prior to events, and monitored during and after the event. Thus, instruments must be in place to monitor continuously for long periods of time. One of the key motivations for establishing ocean observatories is their ability to capture transient events. *ORION, with its ability to provide communication and power to extensive arrays of stationary sensors and mobile platforms, will allow us to observe and sample these transient phenomena, and document more gradual changes that occur over decades within these systems.*

Scientific Priorities

1. Determine the influences of fluid (water, gas, magma) migration and water-column hydrodynamics on chemical and biological systems at and near seafloor spreading centers.
2. Determine the dominant processes controlling gas hydrate dynamics and their environmental, climatological, biological, and geological consequences.
3. Determine the processes that lead to continental margin slope failure, and their consequences.
4. Estimate the mass and energy fluxes between the crust/lithosphere/asthenosphere and the ocean, document how they are distributed in space and time, and determine their consequences.
5. Characterize the composition and activity of subsurface microbes within the oceanic lithosphere and adjacent continental margins, and identify their biogeochemical processes and influences.

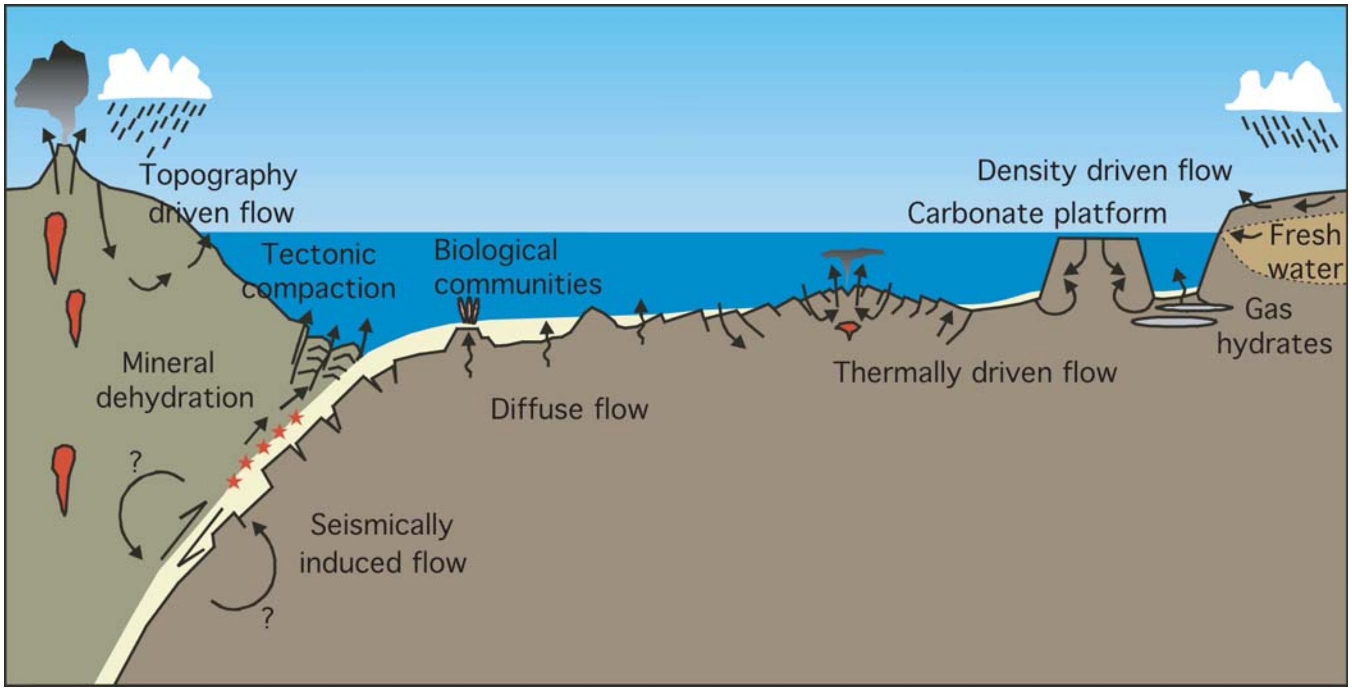


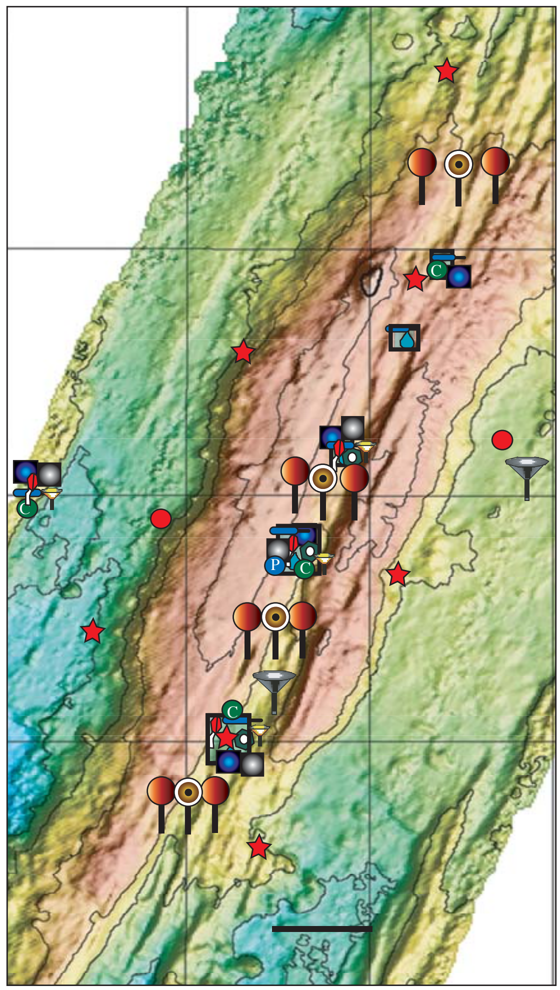
Figure E-1. Subseafloor fluid flow regimes (from JOIDES Hydrogeology PPG Report, 2001, http://poseiden.palaeoz.geomar.de/panels/reports.html). Black arrows indicate water movement. Red blobs are rising melt; red stars are earthquake locations. Half arrows below the red stars indicate the relative direction of movement of the subducting lithosphere and overriding plate.

Example ORION Experiments

How are ridge-crest hydrothermal systems, and the biological communities that they support, affected by volcanic and tectonic events?

Hydrothermal systems along mid-ocean ridge crests can be active for decades given a source of heat and conduits to the seafloor. These systems transfer energy and mass into the deep ocean at different rates, and over different aerial extents, allowing associated biological communities to wax and wane. Evidence from ship-based surveys over the last two decades indicates that occasionally these systems get an extra “kick” from local volcanic and/or tectonic events, resulting in both an increase in the volume of fluids being expelled from the vent site (as event plumes - large plumes of water containing excess heat and minerals indicative of hydrothermal activity) and dramatic changes in the chemistry of the venting fluids. These events are accompanied by the presence of spectacular microbial blooms that result as volatiles and chemical species leached from the rock provide nutrients to microorganisms, and/or as material is flushed out from active colonies in the subsurface. However, because the events typically last only days and event plumes appear to form in hours to days, the association between eruptive-diking events and event plumes is still poorly understood. The formation of event plumes is a matter of considerable debate and has been attributed to the flash cooling of lava flows and shallow dikes or to the ejection of mature hydrothermal fluids from deep within the system.

To understand the processes responsible for the microbial blooms and to quantify the variable fluxes associated with these events, OOI will provide a cable that will support arrays of instruments and mobile platforms along a 20-km-long segment of the Juan de Fuca Ridge (JFR) in the Northeast Pacific Ocean (Figure E-2). Networks of seismometers and geodetic instruments spaced at 200-m intervals will allow scientists to detect and accurately locate an event and define its dimensions and characteristics. Sensors and samplers will be placed within areas of hydrothermal fluid flow to charac-



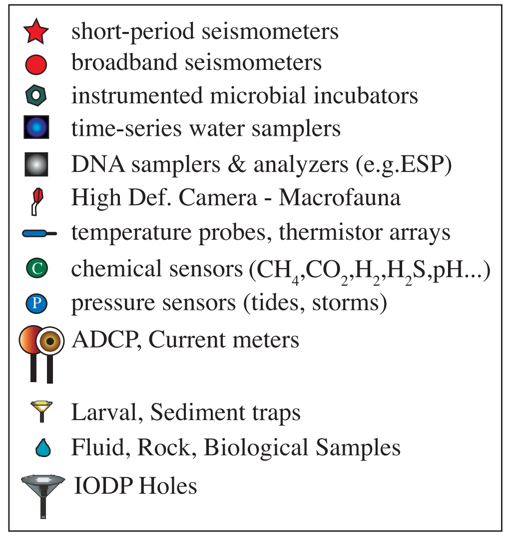
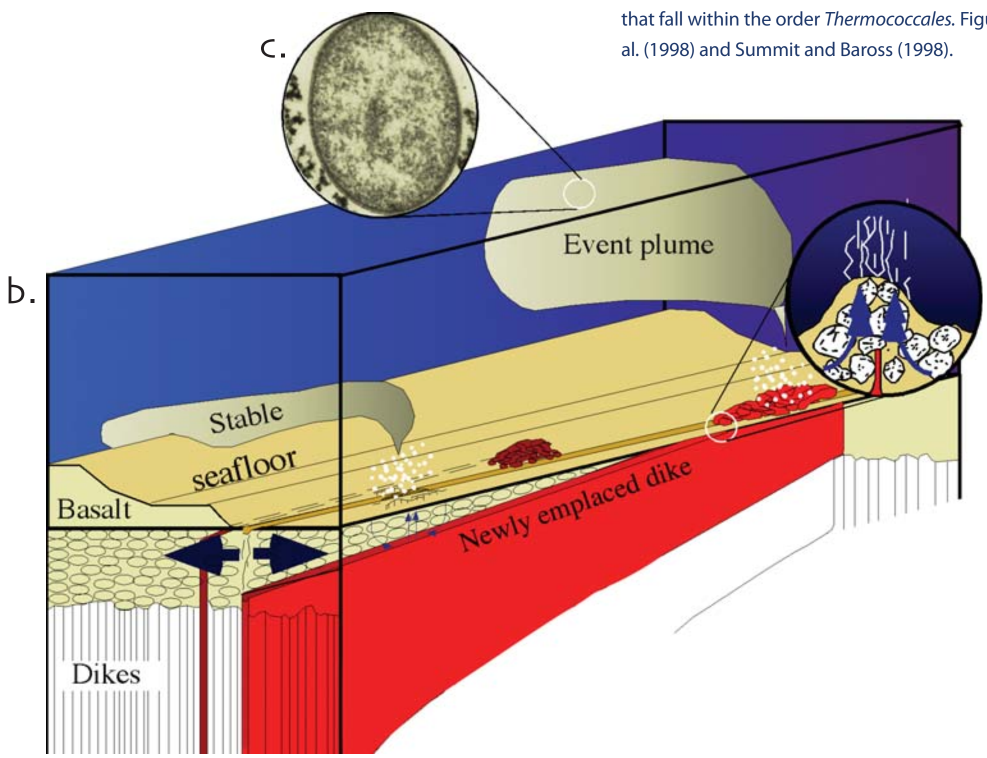


Figure E-2. (a) Proposed location of instrument arrays and stationary sensors together with mobile platforms along a 20-km-long segment of the Juan de Fuca Ridge in the Northeast Pacific Ocean. These instruments and sensors will provide information about environments prior to, during, and immediately following transient events. Figure courtesy of D. Kelley, University of Washington. (b) Schematic diagram of the sub-seafloor, seafloor, and water column above a ridge crest vent site following a diking-eruptive event. Note the event plume (the > 10 km diameter by hundreds of meters thick plume of water containing excess heat and minerals indicative of hydrothermal activity) above the eruption, and the presence of spectacular microbial blooms that result as volatiles and chemical species leached from the rock provide nutrients to microorganisms. Organisms (e.g., as shown in c) have been cultured from event-plume fluids, including hyperthermophiles (organisms that grow best at temperatures higher than 80°C) that fall within the order *Thermococcales.* Figure modified from Delaney et al. (1998) and Summit and Baross (1998).



terize changes in the flow rates, physical properties, chemistry, and microbial content of hydrothermal fluids emanating from both high-temperature and diffuse vents. Stationary camera systems will record the evolving impact of the event on hydrothermal vent sites and macrofauna. Measurements from water-column moorings will constrain the changes in the dimensions and composition of the hydrothermal plumes. Measurements in instrumented boreholes will complement seafloor observations and improve our capability to interpret seafloor observations in terms of subsurface hydrothermal and microbial processes. Because the exact location and characteristics of an event cannot be predicted in advance, real-time data communications are essential so that the sampling and surveying strategies can be quickly modified based on the details of a particular event. Autonomous underwater vehicles (AUVs) and other mobile platforms will be critical for a complete event response because they are the only practical means of surveying extensive areas of seafloor and water column during the early stages of the event. The AUVs will dock periodically at an observatory node to recharge batteries and download data allowing scientists ashore the opportunity to program the next mission based upon their evolving understanding of the event.

Data collected using this array of instruments and sensors will also be able to be used to address a range of other high-priority questions, including: How do the nature and extent of hydrothermal fluid flux evolve in the absence of major magmatic or tectonic events? How do the responses of hydrothermal systems to perturbations at a range of scales provide information about the structural control of hydrothermal systems and/or the nature of the heat source? What are the relations between these changes and the succession of surface and subsurface biological communities? What are the effects of bottom currents and ocean and earth tides on the fluid flow rates from the seafloor and the consequences for chemical and biological systems both above and below the seafloor?

The value of an observatory approach has already been recognized, with the NOAA/PMEL group having established the NEMO observatory on Axial Seamount on the JFR, and the RIDGE2000 program and related efforts supporting multi-year, multidisciplinary observations on the Endeavour segment (JFR) and the East Pacific Rise (EPR) at 9°50'N. The availability of a cable on the JFR, and of buoys in other areas such as on the EPR, would immediately solidify these efforts, allow the inclusion of sensors with large power requirements, and provide the real-time data and response capability that are critical for studying transient events. On a time scale of five years, additional buoyed observatories could be established on the Mid-Atlantic Ridge and the Lau Basin back arc spreading center. In 20 years, we envision a network of over half a dozen ridge observatories including several that are cabled. These might include at least one observatory on each of an ultra-fast and an ultra-slow spreading ridge.

What are the dominant processes controlling gas hydrate dynamics and what are their environmental, climatological, and geological consequences?

Current interest in the resource potential of gas hydrate is based on the growing realization that the methane stored in gas hydrates may constitute one of the largest fossil fuel carbon sources on Earth. However, in order for gas hydrate to be an energy source, the methane must be extracted in an economically viable fashion. A separate but related issue is that gas hydrates may constitute a hazard to seafloor hydrocarbon-producing infrastructure. As warm oil and gas are extracted, heat will inevitably be conducted into the sediments that are in contact with the well bores or pipelines. If the surrounding sediments contain gas hydrate, and it decomposes, dramatic changes in the physical properties of the affected sediments may result in reduced sediment strength, which in turn could produce substantial damage or destruction of facilities. Many slope-failure events observed on continental margins have been attributed to decreases in sediment strength associated with gas hydrate decomposition.

The OOI infrastructure offers the opportunity to evaluate the hazard (slope stability, destabilization of offshore structures) and resource (production test, how much methane is present) potential, and climatic effects (mechanisms for ejecting gas hydrate methane carbon to the atmosphere and ocean) of gas hydrate decomposition. This could be done by carrying out a controlled experiment and continuously monitoring the response (e.g., deformation of the sediments; changes in pore pressure) before and after the decomposition is initiated. An OOI power cable will be used to heat the hydrate in a borehole field. The area in and around the main borehole will be continuously monitored for about one year—within four boreholes surrounding the main hole, at the seafloor, in the water column, and in the atmosphere above the hole. The OOI cable will provide power to the pumps needed to collect gas and fluid samples from the borehole. The central hole will be equipped with an array of electric heating elements and an acoustic source. The four surrounding holes will be approximately 10 m away from the heater hole and about 30 m deep (Figure E-3). Seismic sensors and sources will be configured to allow high-frequency seismic sources to generate ray paths around the heater into the surrounding boreholes. The reduction of gas hydrate content within the affected sediments and the changes in the thermal conditions within this well field will be tracked using a series of sensors in the boreholes and on the seafloor. Deformation of the sediments will be sensed with tilt meters. Pore-pressure sensors will establish whether local overpressures develop as a result of gas pressures and seals. The experiment can be carried out at Hydrate Ridge in the Northeast Pacific. Seismic, drilling (ODP Leg 204), and other survey information from this region suggest that there is a substantial amount of gas hydrate-bearing sediment buried in the shallow subsurface.

Are most submarine slope scars formed by catastrophic slope failure from hydrate-related gas venting or by slow creep and/or numerous smaller slope-failure events?

Submarine scars that are produced by the mechanical failure of the slope sediments are common features on continental margins. Some of these scars were probably produced during individual catastrophic events that may have generated tsunamis. Other slide scars, however, may have been generated by numerous smaller events with slow creep accounting for the majority of the mass movement. Very large or even

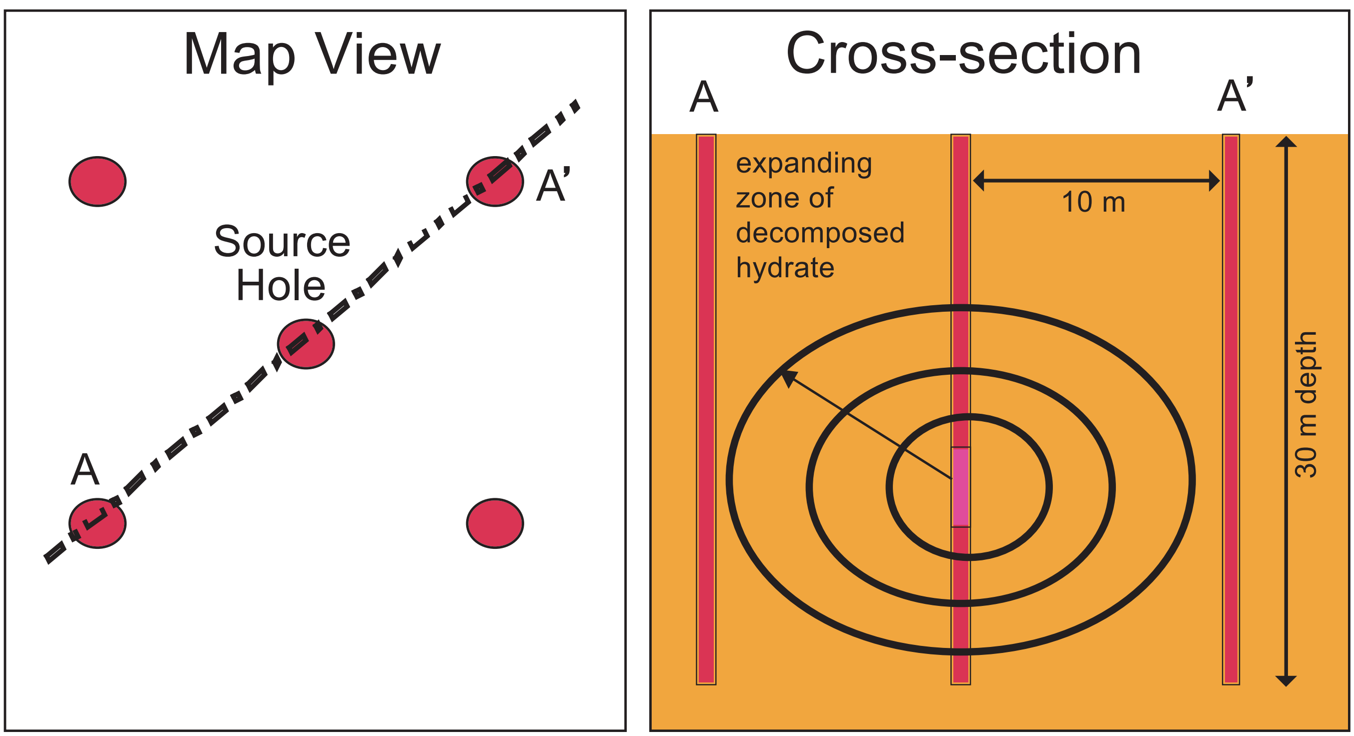


Figure E-3. A proposed configuration of boreholes for carrying out a controlled experiment on gas hydrate decomposition. An OOI power cable will be used to heat the hydrate in the center source borehole. Four surrounding holes will be approximately 10 m away from the heater hole and about 30 m deep. The area around the borehole will be monitored for a year to track changes in gas hydrate content within the sediments, thermal conditions, sediment deformation, and other properties.

moderate slides may have a profound effect on destabilizing seafloor structures, such as deep water oil platforms or trans-atlantic cables. In addition, destabilization from slide events could result in abrupt gas release from gas hydrate deposits on the continental slopes, which could contribute to global warming and abrupt climate change (Shepard and Whelan, in press). Unfortunately, there is little observational evidence to show which of these two modes of slope failure (catastrophic versus slow creep) predominates in scar formation. Observatory technologies provide the ability to resolve this issue and would help in assessing risks to infrastructure installations on the seafloor.

Mechanical failures of the slope reflect changes within sediment sections that weaken the sediments so that the resistive forces that had previously kept the material in place were exceeded by the gravitational pull on the sloping sediment mass. Sediment weakening can result from variations in the pore-pressures within sediment column, seismic accelerations, wave loading associated with storms, gas hydrate formation and decomposition, oversteepening due to continued sediment accumulation, and progressive failure of the sediments at the toe of the slope that remove the downslope support. However, there are few data to evaluate any of these mechanisms. Thus, it is critical to obtain information on the timing and magnitude of conditions associated with these events.

To distinguish between catastrophic and slow failure, we will install a network of seafloor tilt, pore pressure, and geodetic stations to monitor movement of materials on the sole of a slide scar and the adjacent sediments that are likely to be the next to fail (Figure E-4). The potential contribution of seafloor gas hydrates and their associated seeping gases on this process could be evaluated by carrying out the experiment in a well characterized gas and gas hydrate rich area, such as the Peru Margin. The absolute slope failure rates will be determined by making geodetic measurements that monitor the position of the nodes. It is now possible to measure the absolute positions of the individual nodes to better than meter accuracy and the relative movements to better than 10 cm. Tilt meters can accurately determine the timing of movements. Surface moorings and a seafloor seismic observatory (presumably deployed for other purposes) will allow the correlation of seismic and unusual wave-height events to be monitored.

This surface network will be augmented by borehole observatories (at intervals of tens to hundreds of meters, depending on the specific slide feature) to define the conditions within the slide fail surface and to establish whether perturbations in subsurface conditions are likely to stimulate changes in the mechanical strength of the sediments. These boreholes will contain pore-pressure and tilt sensors, chemical sen-

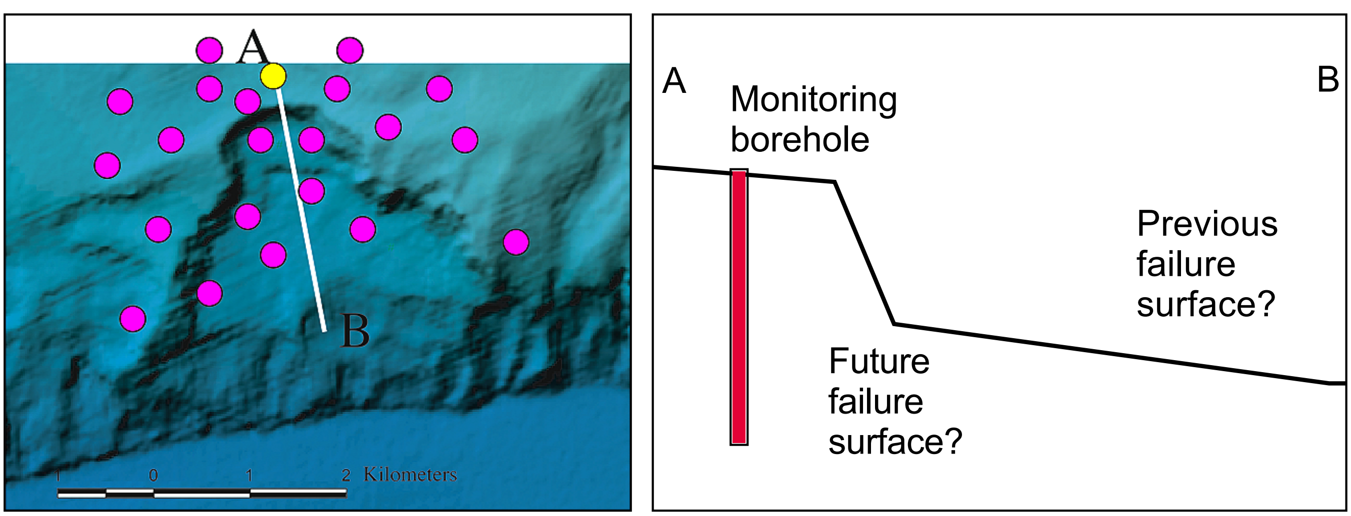


Figure E-4. Schematic diagram showing the borehole (yellow dot) and the network of seafloor tilt, pore pressure, and geodetic stations (pink dots) to monitor movement of materials on the sole of a slide scar and the adjacent sediments that are likely to be the next to fail.

sors to establish whether there are significant concentrations of methane to support gaseous gas and/or gas hydrates, and thermal and pressure sensors to indicate that the gases and/or pore fluids are advecting along this surface. When the seafloor nodes are coupled with instrumented boreholes that pass through the depth of the main sole of the slide scar, one can establish whether and when conditions occur that will produce the failure in the subsurface to trigger these events.

Data from these observatories will also provide synergy for complementary studies and post-event responses. Repeat mapping can be done to compare detailed bathymetry before and after these events. Arrays of sensors can be used to locate sites of most recent failure, which will allow focused geochemical and biological studies to look at the consequences of the failure. Because the removal of an appreciable amount of surface sediments is likely to disrupt methane-charged sediments and methane hydrates in the seafloor, new gas seeps may be generated, resulting in colonization of chemosynthetic biological communities on the freshly exposed seafloor. In addition, this work will show if and how gas seepage can trigger additional slides potentially leading to feed-back effects and abrupt release of methane from seafloor gas hydrates.

What are the abundance, diversity, and metabolic activity of microbes within young oceanic lithosphere and how does this biosphere vary in space and time?

The oceanic lithosphere contains the largest aquifer system on Earth, and studies carried out over the past two decades have drawn attention to the presence and significance of a subseafloor biosphere. However, very little is currently known about life within this biotope, and about energy generation in the absence of light. Recent advances in molecular techniques have led to evidence for primary productivity occurring in a range of environments including in marine sediments (shallow and very deep) and within the oceanic crust. Investigations of these environments are needed to determine the sources of energy (e.g., the specific chemosynthetic reactions that are being used), amounts of energy available, and the size of the ecosystems. The energy and ecosystems supported in these environments may contribute to the global carbon budget.

One environment of particular interest is within young oceanic lithosphere, however, its investigation requires controlled access to the environments of interest and the ability to carry out *in situ* observations. Drilling at multiple scales (horizontal and vertical) can be done to allow controlled sediment, water, and rock sampling to characterize microbial diversity and abundance. Environmental data (e.g., permeability, volatiles, fluids, temperature) can be collected simultaneously. After sediment and rock have been extracted, the open boreholes can then be instrumented, and used as *in situ* observatories to characterize microbial metabolism in the subsurface. ORION, and the cable across the Juan de Fuca plate, will provide the power to make the required *in situ* measurements.

To characterize the deep, subseafloor biosphere, borehole observatories will be emplaced first within preexisting holes that have been logged by the Ocean Drilling Program, on the flank of the Juan de Fuca Ridge. Initial measurements have been done, and more will be needed, to determine the nature and distribution of the aquifer (Where are the fluids and how are they venting? Is the formation over pressured or under pressured?). Once this is established, a system of advanced borehole seals (or "ACORKs") will be installed. These ACORKS will have multiple packers that will seal off different levels within the borehole and instrumented chambers, to monitor fluid properties (e.g., chemistry, pore pressure, temperature), the nature of the microbes, and a variety of strata for colonization experiments (Figure E-5). Using chemical tracers, pumping experiments from each chamber can be carried out (e.g., isotopically labeled carbon) and push-pull experiments ("push" or add a component into a system or chamber, let it sit for a period of time, then withdraw or "pull" fluid out of the system of chamber and observe the differences in chemistry) to see what the activity of the microbes are *in situ* (e.g., to examine metabolic activity associated with methanogenesis).

It is important to be able to access in real-time the fluids and the microbes in each chamber. Future experiments will include use of retrievable incubation chambers that preserve the conditions and microbes *in situ* from depth. Pumping experiments from each chamber will allow fluids and microbiological material to be brought to the surface for analyses

In Situ Monitoring and Sampling Beneath the Oceanic Crust: Advanced CORK Systems

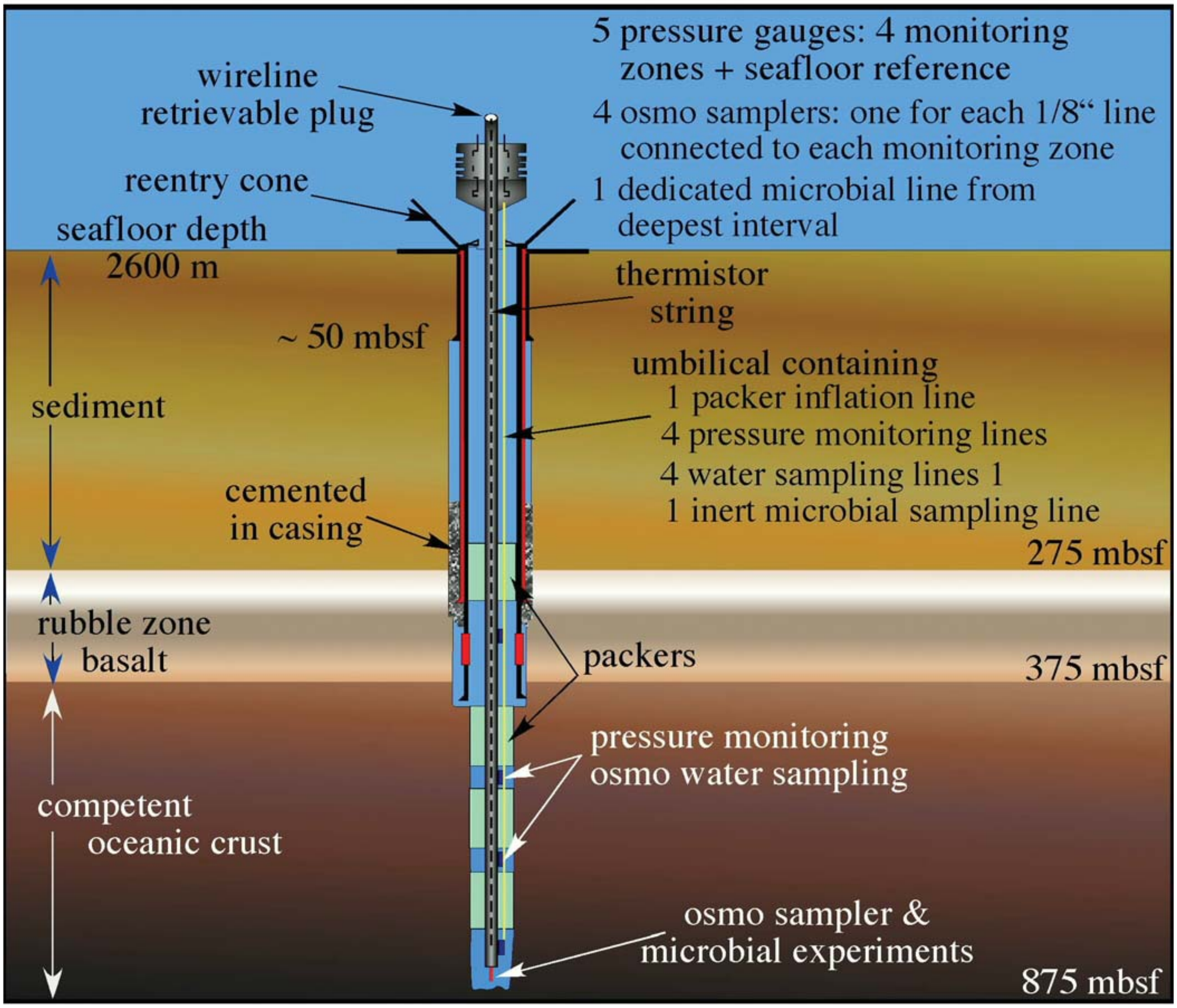


Figure E-5. Advanced borehole seals (or "ACORKs") have multiple packers that seal off different levels within a borehole drilled by the Ocean Drilling Program or Integrated Ocean Drilling Program. Instrumented chambers monitor fluid properties (e.g., chemistry, pore pressure, temperature), the nature of the microbes, and a variety of strata for colonization experiments. (Osmo samplers are samplers that can make fluid collections continuously for days to weeks; mbsf = meters below the seafloor.)

through mass spectrometry and biological analyzers (e.g., the Environmental Sample Processor (ESP); DNA on a chip, flow cytometry). A future, exciting capability would be the development of downhole fiber optics coupled to analytical systems that would allow characterization of the environment and microbial colonies without having to bring material to the surface. Adaptable analytical systems that could be used with fiber optics include micro Raman systems (to allow analyses of proteins, organic compounds, dissolved volatiles), LIBS (elemental chemistry), DAPI stains with illumination, enzyme assays, and FISH. Through these analyses, quantitative characterization of microbial abundance, metabolic activity, and environment can be made.

Critical Issues

The major challenge that must be met as we move forward to investigate the dynamics within fluid-dominated portions of the seafloor is development of tools, sensors, and samplers capable of working *in situ* for long periods of time in harsh environments. Some sensors and tools already exist, such as those needed for monitoring temperature, pressure, and some aspects of *in situ* chemistry, as well as downhole cameras and sampling pumps. However, there is still a large need for development of chemical and biological sensors for use in both hot and cold environments. Issues related to biofouling, corrosion, calibration, and drift need to be tackled (see summary in Daly et al., 2004). Techniques for accessing the subsurface biosphere in its pristine (undisturbed) state also need to be developed. Further development of AUV capabilities is also needed. Vehicles could be developed with short tethers or with communication by blue-green lasers to facilitate continuous, real-time control by scientists. The development of MEMS (micro-electro mechanical systems) or smart-dust technology may eventually lead to arrays of sensors that could be deployed from an AUV to provide high-resolution images of water column structure (e.g., hydrothermal plume structure above an eruption).

A secondary challenge involves data management and access. Data will need to be made available to the science community as soon as possible, and with tools to analyze and visualize data. Issues related to compatibility across data types and across platforms will need to be dealt with. Issues related to sequence data will need to be resolved. At present, data on sequences are so valuable to biotechnology firms that researchers are unwilling to release data.

Outreach

Areas of active fluid flow from the seafloor provide environments that support lush biological communities at depths where the seafloor, in the absence of fluid flow, appears relatively barren. The biological communities found at seafloor hot vents and cold seeps are unusual, viewed as exotic, and have attracted the interest not just of scientists and educators, but of the larger public. The public wants to know and understand why these animals can thrive at these depths in the absence of sunlight. Vent sites thus provide excellent "hooks" to entrain audiences and to encourage the public to learn more about the oceans. For example, comparisons of biological communities present at sites of fluid flow with those distal to flow can be made, and intriguing modules developed to teach non-scientific audiences about the dynamic interactions among physical, geological, chemical and biological processes occurring within the ocean depths.

Formal Education: ORION scientists and educators can work together to develop modules that fit within school curricula at elementary and secondary levels. Fluid flow sites can be used to discuss important topics within Earth science, physics, chemistry, and/or biology, such as energy transfer, unusual biological communities, chemosynthesis, engineering, and land-based analogs of hydrothermal systems (Yellowstone, Iceland). Students in classrooms will be able to log onto web sites and access and use real-time *in situ* images of biological communities and growing mineral deposits, and real-time data streams of temperature, chemistry, fluid flow rates, and pressure. For the perturbation experiment described above, students could be involved in turning on the heater, and periodically watching the response of the system by looking at data from the various sensors, and by observing images of organisms at the seafloor before and after the heater is turned on.

Informal Education: A number of web sites on active venting at hot and cold seeps already exist that entrain the public and increase their awareness of the ocean, and of the dynamic processes that occur at depth. The existing sites frequently follow a cruise, posting updates and showing snapshots of data. As sensors, samplers, and other tools are emplaced, these data streams can be made available to the public, with updates of processed or visualized data made available on a regular basis. Museums and aquaria could develop programs such as "adopt a sensor," or could highlight the use of new cool tools. Opportunities also exist for video conference seminars with remote universities on such complex topics as life in the deep sea, and how to carry out culturing experiments in remote environments.

The Key to Success

The projects described here are ambitious; require development of new robust sensors, tools, and techniques; must utilize scientific expertise from researchers with a wide range of expertise in chemistry, physics, geophysics, geology, geochemistry, biochemistry and biology; and must be carried out collaboratively. Each of the projects mentioned will benefit greatly from the complementary interests shared by other national and international programs, including those focused on the mid-ocean ridges and back-arcs (RIDGE2000, InterRidge, JAMSTEC, ESONET, MOMAR), on the ocean margins (MARGINS), and on the subsurface (IODP). Such collaboration has been strongly encouraged by experts from both the oceanographic and atmospheric communities in a recent workshop report entitled, *Role of Ocean Methane and Gas Hydrates in Global Climate Change* (Shepard and Whelan, in press).

Fluid-Rock Working Group

- Patricia Beauchamp, Jet Propulsion Laboratory
- Karen Bemis, Rutgers University
- Kevin Brown, Scripps Institution of Oceanography
- Richard Camilli, Woods Hole Oceanographic Institution
- Mathilde Cannat, Institut de Physique du Globe, Centre National de la Recherche Scientifique
- Alan Chave, Woods Hole Oceanographic Institution
- Steve D'Hondt, University of Rhode Island
- Charles Fisher, Pennsylvania State University
- Daniel Fraser, University of Manitoba
- Patricia Fryer, University of Hawaii
- Edward Geary, Colorado State University
- Henny Groschel, University of Miami
- Kim Juniper, Universite du Quebec, Montreal
- Deborah Kelley, University of Washington
- Marvin Lilley, University of Washington
- George Luther, University of Delaware
- Brian Midson, National Science Foundation
- Lauren Mullineaux, Woods Hole Oceanographic Institution
- German Ojeda, Coastal Carolina University
- Charles Paull, Monterey Bay Aquarium Research Institute
- Morgan Richie, Ocean Institute
- Jozee Sarrazin, Institut français de recherche pour l'exploitation de la mer
- Debra Stakes, Monterey Bay Aquarium Research Institute
- Jean Whelan, Woods Hole Oceanographic Institution
- William Wilcock, University of Washington

F. Food Webs and a Changing Ocean

W. Paul Bissett (Moderator), Lisa Campbell (Rapporteur), Brad de Young (Rapporteur)

Marine food webs represent a series of nonlinear trophic interactions that are modulated by a complex set of climatic (global warming, storms, winter cooling-summer heating), pelagic (mixing and stratification), lithospheric (nutrient weathering, volcanic eruptions), and anthropogenic (terrestrially derived macro and micro nutrients, buoyant plumes, human grazing pressures) forcing functions. Often these food webs appear to be in an equilibrium state with the environment, however, they can undergo sudden and dramatic transitions. Understanding when and how food webs shift from one equilibrium state to another has been richly explored in theory, though understanding how ecological regime shifts occur in the oceans is still widely debated. Unfortunately, until there is a comprehensive understanding of food webs, interpretation of their observed shifts will be mired by multiple competing hypotheses, precluding any ecosystem-based management response. Currently, many food webs appear to be undergoing major shifts. Fishing pressures have depleted globally most of the world's large fish (Myers and Worm, 2003). Warming trends in polar seas are being accompanied by shifts in phytoplankton (Moline et al., 2004) and zooplankton communities (Loeb et al., 1997). Changes in macronutrient ratios may be altering the relative composition of the phytoplankton communities in coastal ecosystems (Hallengraef, 1993).

Unfortunately, our ability to differentiate natural trends in food webs from human-induced changes is rarely possible. Thus, scientists are forced to speculate as to whether regime shifts have occurred and whether these shifts are reversible. For example, reversible regime shifts due to the warming trend associated with the Pacific Decadal Oscillation (PDO) may help increase the number of coccolithophores relative to diatoms in the Bering Sea. If over-fishing causes an alteration in the trophic pyramid, will reducing the fishing pressure allow previous stocks to return? Or, does the food web, once altered, change forever?

Scientific Priorities

1. Quantify the top-down versus bottom-up processes in controlling fluctuations at the base of the food web.
2. Understand the initiation, maintenance, and impacts of Harmful Algal Blooms (HABs) on coastal ecosystems. Quantify the relative role of the physical environment versus that of grazer escapement in controlling HAB species.
3. Understand what mediates changes in grazer communities associated with climatic indices (such as the North Atlantic Oscillation and Pacific Decadal Oscillation).

ORION will facilitate research on food webs by providing much-needed long, continuous spatial time series. Observatories' interactive capability will enable adaptive sampling, which has not been possible to date because of the great time lag in getting to sea. The ability to maintain a continuous spatial presence in the ocean will allow scientists to propose experiments not possible before.

Example ORION Experiments

What regulates the initiation, maintenance, and impact of HABs? How important is the role of escaping grazing pressures via toxin production in controlling HABs?

- Hypothesis 1. The aggregation of toxic phytoplankton biomass is dominated by physical accumulation processes rather than biological processes related to *in situ* growth.
- Hypothesis 2. The escapement of predation by HAB phytoplankton is controlled by toxin production and is the main form of grazer avoidance.
- Hypothesis 3. Toxicity is a constant function of biomass, and as the population increases, there is an increase in the toxin concentrations, which ultimately yield a critical mortal threshold for grazers.
- Hypothesis 4. Toxicity is an inducible expression related to total biomass, and as populations increase, there is an induction of toxin production, which in turn leads to a critical toxin threshold.

HABs are dynamic events resulting from a unique, but poorly sampled, set of physical, chemical, and biological forcing conditions. A large fraction of the world's oceans are affected by an increase in the frequency of harmful algal blooms (HABs); however, the causal mechanisms (possibly including climate shift or anthropogenic nutrient release) are a subject of intense debate. The difficulty is in understanding how slow-growing harmful algae can increase to sufficient numbers that their toxin levels can perturb the entire marine ecosystems (even though most other phytoplankton taxa grow at faster rates). Although it is possible to predict that some red tides will occur in a particular region in a specific season, it is very difficult to predict exactly where and how large the HABs will be. For example, the West Florida Shelf has been the site of toxic blooms of *Karenia brevis* (>1 x 10^4 cells l^{-1}) for 42 of the 49 years between 1954 and 2002 (1954-1998 data from Florida Marine Research Institute [FMRI] 2000; 1999-2002 data from K. Steidinger, FMRI, per comm.). However, even though there is a statistically significant possibility that a red tide will occur in this region, predicting exactly when and where these *K. brevis* blooms occur is not currently possible.

An ORION project designed to study the causal nature of HABs would require a long-term commitment in order to (1) observe multiple HAB initiation-maintenance-senescence events, (2) avoid temporal aliasing resulting from undersampling, and (3) assure an interdisciplinary focus allowing trophic interactions associated with HABs to be studied. Additionally, it is important to have an adaptive rapid-response capability for characterizing the advection of HABs when a bloom has been identified. This effort would require regional infrastructure (including moored, AUV, ship, aircraft, and satellite platforms) to provide integrated data streams with sufficient spatial and temporal resolution over broad regions of the coastal ocean. Because HABs are typically seasonal events, field efforts would have to be maintained for a large number of years. The sampling frequency would need to be sufficient to resolve the hydrography and physical circulation on the continental shelf (i.e., horizontal <1 km, vertical <1 m, and temporal <1 day over annual to interannual time periods). This resolution could be achieved by a combination of HF radars, moorings, long-duration mobile platforms, and high-resolution aircraft and satellite observations (Figure F-1). Upon finding initiation conditions, a small fleet of smart AUVs, coupled with higher-resolution aircraft remote sensing and ship-board process studies, would swarm to the study site to conduct high-resolution (horizontal <10 m, vertical <10 cm, and temporal <1 hr) sampling of phytoplankton physiology, toxin production, and grazing dynamics.

Priority measurements will be similar to other physical circulation studies, as well as biogeochemical carbon cycling studies. Therefore, high-resolution hydrography, nutrients, and physical circulation (including turbulence) measurements are central to this problem. Specific identification of phytoplankton species and the community of zooplankton grazers will be a significant key technology that needs to be developed and deployed. Using the Pioneer array concept (Figure F-1),

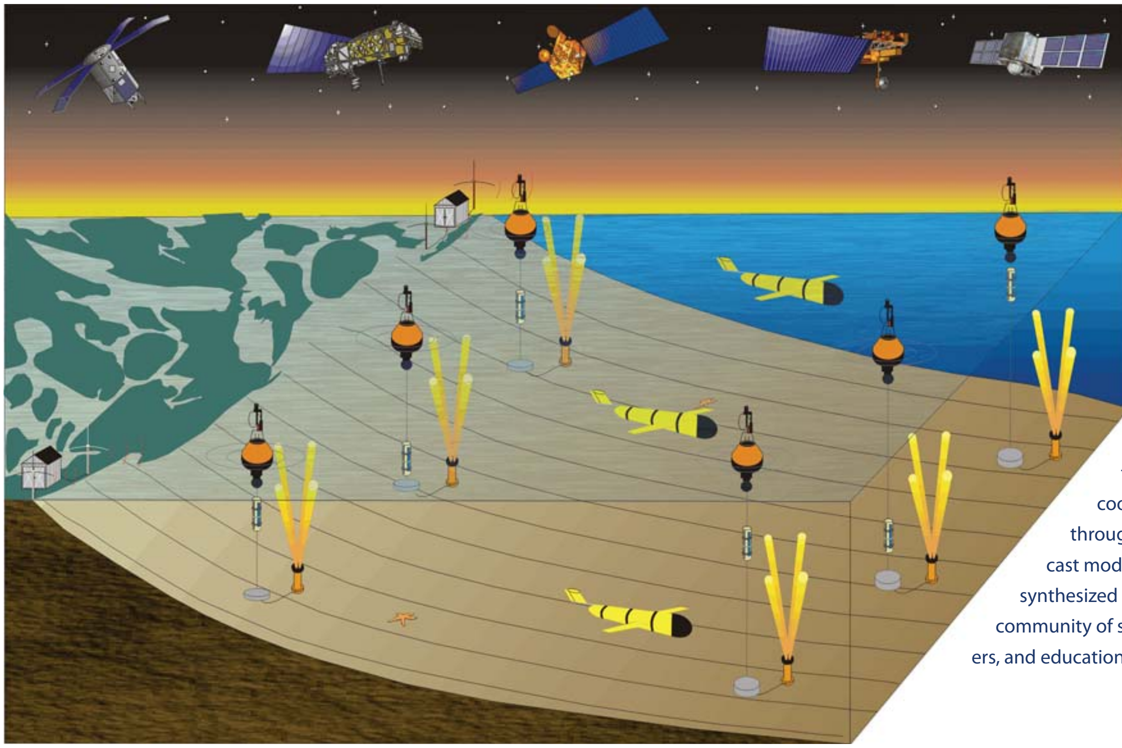


Figure F-1. A potential Pioneer array that would provide a well-sampled section of the coastal ocean on order of 1000 to 10,000 square kilometers. The data for scientists would be provided by several platforms that include satellites, aircraft, moorings, shore-based radars, and long-duration autonomous platforms. Data from these systems would be coordinated and analyzed through real-time nowcast/forecast modeling programs to provide synthesized ocean products to a wide community of scientists, resource managers, and educational facilities.

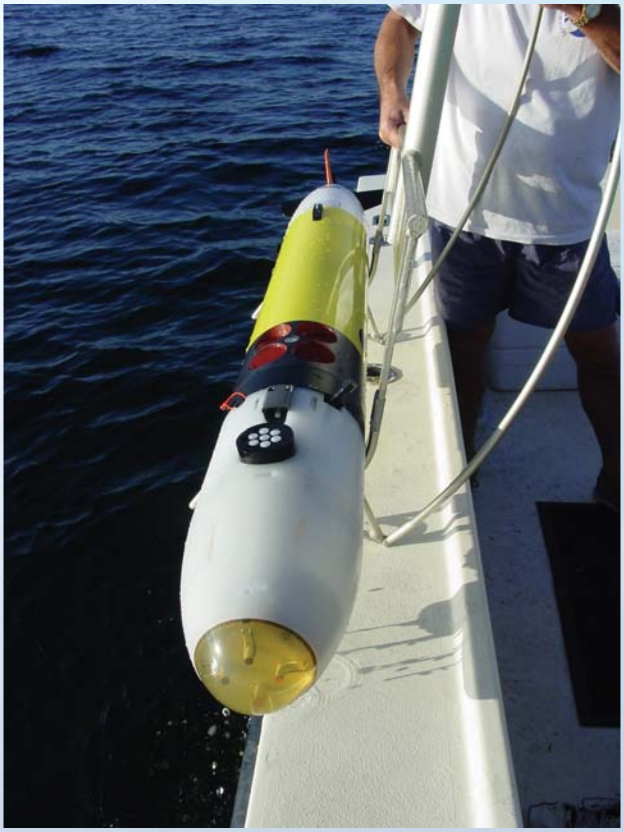
phytoplankton identification may occur *in situ* via spectroscopy on AUV and moored platforms. In addition, imaging spectroscopy by aircraft and satellites may also provide spatial coverage over the broad regions of the shelf, which will fill in the areas not covered by the slower moving *in situ* mobile platforms. Additional species-specific genomic sensors are rapidly evolving and may be available to put into operation over the large spatial scales. The use of high-resolution, vertical, *in situ* instruments will be critical to addressing the possibility of initiating conditions occurring in thinly structured layers, which may not be adequately sampled by moorings with large discrete spacing in sensor packages. The identification of zooplankton may require the use of both optical and acoustical sensors; future technological developments will fuse optical and acoustical data streams for better species identification.

Once a HAB has been identified, process studies will then be needed to quantitatively describe the interactions between toxic phytoplankton and grazers. This process study would occur within a higher-resolution sensor array, would sample at higher spatial and temporal frequencies, and include the ability to move with the bloom in order to study the evolution of the trophic dynamics between autotrophs and heterotrophs. This high-resolution array would have to be rapidly deployable with the same base sensor suite as the Pioneer array in order to maintain consistency between the two arrays. The high-resolution array, called here the RAPidly Triggered Observation Response (RAPTOR) Array (Figure F-2) will also include sensors that will focus on the interactions between the toxic algae and the rest of the food web. Although still under development, some of these new sensors may include genomic identification tools and genomic tools that identify basic physiological rate processes, which will be particularly important for elucidating toxin effects on the food web. In addition to traditional means of phytoplankton and zooplankton abundance and rate measurements, *in situ* visual identification by optical imaging should also be included. These adaptive networks will need to drift and swarm with their sensor packages to keep studies focused on interior

Box 6. Technology Advances: Autonomous Underwater Vehicles for Spatial Validation of Ocean Remote Sensing Products

Contributed by Mark Moline, California Polytechnic State University, and Gary Kirkpatrick, Mote Marine Laboratory

Since the late 1970s, ocean color satellites have revolutionized our understanding of fundamental biological processes in the ocean. While the operational success of these platforms has been unmatched, there has been a chronic difficulty developing and applying algorithms in coastal oceans for retrieval of basic optical constituents due to their optical complexity (i.e., chlorophyll). The distribution of optical constituents, such as phytoplankton, detritus, colored dissolved organic material (CDOM), and inorganic particles in coastal regions are influenced by terrestrial inputs, local atmospheric forcing, and bottom bathymetry, and can vary rapidly in time and space. Single-point measurements for calibrating/validating remote sensing data have worked well in open-ocean environments because of its relative homogeneity; however, the optical complexity and short correlation/decorrelation length scales of coastal environments require measurement and validation across significant optical gradients to fully characterize a region and evaluate algorithms. Additionally, these optical gradients or fronts often represent distinct separations in biological communities and chemical properties. Autonomous underwater vehicles (AUVs) will play a central role within the ORION network in sampling evolving sub-kilometer-scale features in the ocean that are poorly described by single-point measurements.



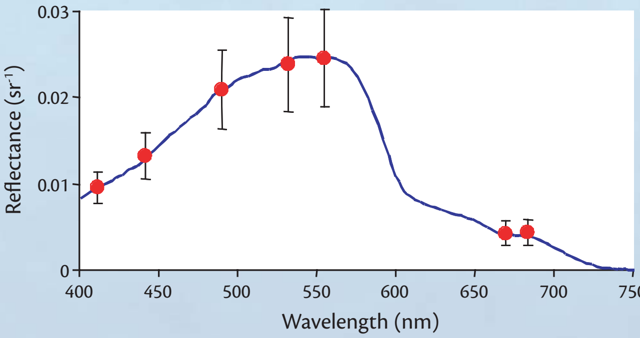
REMUS AUV with multispectral radiometer on the top of the forward section.

Advances in AUV technology have produced platforms that offer versatility in size, mission duration, speed, navigation, power, payload capabilities, and adaptive capabilities to systematically sample significant spatial domains in near shore environments (Rudnick and Perry, 2003). Outfitting these vehicles with optical sensors provides the potential for a new method of ocean-color validation in coastal oceans. These measurements are ready to be deployed as part of ORION networks.

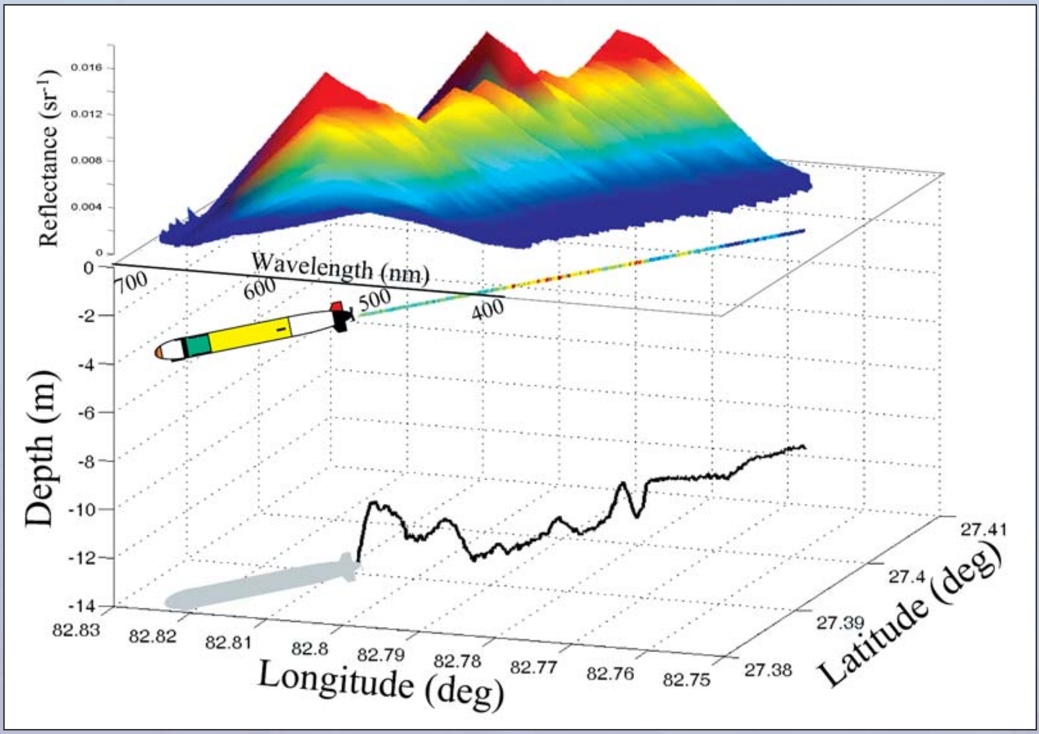
A REMUS AUV, augmented with multispectral upward irradiance and downward radiance sensors to provide spatial remote sensing reflectance and attenuation, allows for near-synoptic spatial validation of aircraft and satellite ocean-color sensors (figure, above). A precondition for the application of AUVs for ocean-color validation is the stability of the underway platform. Data from multiple deployments in California up to 20 km offshore and in varying sea state conditions (n > 106) show the vehicle to be very stable, with pitch of 0.6° and roll 1.5° from center, well within the limit of 10° recommended by the SeaWiFS protocols (Mueller and Fargion, 2002). In calibration experiments, the AUV's measurements of surface spectral remote sensing reflectance correlated well with the simultaneous measurements made by an *in situ* hyperspectral buoy (Satlantic HS-TSRB), which is often employed for validation exercises (figure, opposite, top).

A deployment off the coast of Florida in November 2003 shows the efficacy of the vehicle in characterizing variability in spectral water-leaving radiance (figure, bottom). Here the variability in the surface signal is primarily due to the bottom bathymetry, highlighting the effectiveness of this single platform in not only measuring the light field but also able to measure *in situ* constituents and bathymetry.

AUVs now offer near-synoptic spatial validation of remote-sensing products in the coastal ocean, and will be an important technology within the ORION network. This application will provide the means for assessing the space/time dimensions of gradients that are poorly sampled by point measurements. The influence of these features on coastal processes represent a key scientific focus of the ORION program.



Comparison between the REMUS AUV multispectral reflectance (n=6000; red) and the mean reflectance from a hyperspectral surface buoy (blue). AUV data were spatially averaged around the buoy location with the buoy data temporally averaged over the AUV deployment period.



Deployment of the REMUS AUV off of the West Florida Shelf in November 2003. Shown here are the AUV measurements of spectral reflectance (surface contour), chlorophyll a (trace behind vehicle), and bottom bathymetry (black line) along an east to west offshore transect. Data like these demonstrate the ability of AUV platforms to simultaneously measure the *in situ* light fields as well as the constituents that affect light attenuation and propagation that are critical for validation of, and algorithm development for, remote-sensing products.

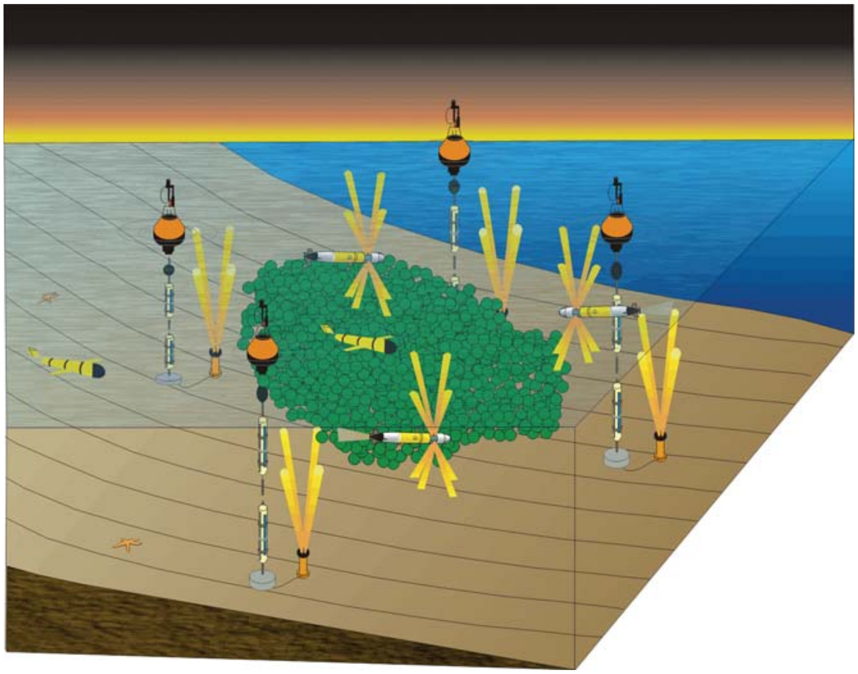


Figure F-2. Higher-resolution observation and modeling programs (order 100 to 1000 square kilometers) will be focused on ecological trigger events that demand adaptive response. The exact placement of research teams and instrument deployments will be based on real-time data so that assets can be strategically placed to answer specific questions. In this case, a harmful algal bloom has been located by the Pioneer array, and has triggered the adaptive deployment of a RAPTOR arrays (RAPidly Triggered Observation Response). These arrays will include instrumentation for physiological and basic stock measurements.

patch dynamics, while at the same time quantify advective and diffusive processes at the edges. Process studies conducted in this manner will specifically address the above hypotheses.

There are programs that have been studying HABs for years, including the national ECOHAB and MERHAB, as well as the international GEOHAB program. These programs provide a rich basis of understanding for many site-specific phenomena. The sensors and platforms needed for the ORION effort will certainly build upon these programs, as well as others such as the ALPS initiative, OOI Pioneer arrays and Endurance lines. The deployment of future HAB monitoring arrays will also be assisted by modeling efforts to develop regional optimal deployment schemes, for example, the Observing System Simulation Experiments (OSSEs). The ORION effort to study food web dynamics will thus build upon years of previous study and infrastructure, and should be viewed as a link to national and international programs focused on the assessment and management of HABs.

What mediates changes in grazer communities associated with climatic indices and how does that impact the overall productivity of ocean food webs?

- Hypothesis 1. Changes in systematic mixing and stratification drive fundamental shifts in autotrophic and heterotrophic communities.
- Hypothesis 2. The strength and frequency of storm events drive fundamental shifts in food-web structure and dynamics at short time scales; the increase in variance may also lead to changes at much longer time scales.
- Hypothesis 3. Changes in autotrophs drive changes in grazers. (This could be considered the general bottom up question, pointing up to grazers.)
- Hypothesis 4. Changes in grazers drive changes in autotrophs. (This could be considered the general top down question, pointing down to autotrophs.)

Although climate indices serve as ready markers of the external forcing that influences the food webs in the ocean, it is recognized that these indices reflect the dominant modes of variability upon which higher-frequency processes operate. Previous expeditionary cruise sampling programs have provided us with much insight into food web processes, but it is difficult to integrate these types of programs into a general understanding of longer-time-scale variability. In addition, data aliasing, and our inability to simultaneously measure at large spatial scales, have led to data sets that cannot be used to address the key hypotheses. The data have led us to understandings that are limited in applicability, and point to the need for new infrastructure to address the hypotheses listed above.

ORION presents the opportunity to make simultaneous, integrated biological, chemical, and physical observations at time scales that will minimize aliasing and lead to a greater understanding of the long-period (decades) problems that we now recognize as dominating variability in marine ecosystems. We have rarely been able to properly sample a single cycle of variability, and at no time have we been able to achieve this sampling at the basin or regional scale, which is unfortunate as it is this scale that this variability occurs. The ability to simultaneously make measurements of physical, chemical, and biological properties, particularly those of zooplankton, over large temporal and spatial scales that would reduce or eliminate the aliasing effects would be a tremendous boon to the study of food web dynamics. In particular, sampling of gelatinous zooplankton, for which we have only scattered and very incomplete data, would allow for observations spanning the full trophic range of the marine food web. Our responses focused on the Pacific basin, but we would have arrived at very similar answers for the Atlantic Ocean and/or the polar seas.

The time scales of interest are primarily seasonal to interannual and decadal. To address some of the key temporal and spatial aliasing issues, adaptive sampling will be an important component because a fixed array may miss some significant events. We could foresee beginning with a basic fixed array, or grouping of lines, that is supplemented by mobile platforms (satellites, ships, underwater vehicles, airplanes) and an adjustable array that can be deployed to address important events (e.g., expanding detailed sampling in key areas during an ENSO event). We would like to be able to measure both in the biogeographic province, and at its boundary (e.g., along the northern California-Oregon coast, Juan de Fuca, and Gulf of Alaska), perhaps filling in between the lines with AUVs to define distribution shifts (Figure F-3). The proposed regional array in the North Pacific sits at the primary northern boundary between biogeographic provinces and could provide measurements of biogeographic shifts in response to changing physical conditions and forcing. We suggest beginning with a program to measure the California Current System food web response to El Niño. This has the advantage of being able to supply food-web response to climate forcing over a shorter time period than the PDO. It would also be sensible to start by deploying new sensor systems on single-point moorings in key locations.

Core sensors identified for this research effort include sensors for obtaining hydrographic water properties, nutrients (from low to high concentrations), and high-resolution profiles of these properties in euphotic zone—dissolved gases (N_2, O_2, CO_2), CDOM, chlorophyll, particle concentration, and spectral light data. In addition, it is recommended that optical and acoustic characterization of phytoplankton and micro, meso, and macro zooplankton be completed, such that sensors measuring the abundance of these grazers could be included into the core suite. We would also need to develop additional sensors to measure rates and processes of food webs, particularly at higher trophic levels. Biological and chemical sensors have lagged behind sensor technology for physical oceanography and a significant part of the ORION effort may be devoted to developing sensors intended to make the necessary measurements for food web studies. As noted above, our ability to measure gelatinous organisms is very limited; we need techniques to make these measurements. It was thought that a particular ORION advancement may be the combination of acoustic and optical technologies into sensors specifically designed to study trophic interactions. In addition, advanced 3-D acoustics may allow mapping of organisms and interactions through space, something that presently requires a vehicle. This development may permit us to see predator-prey interactions, encounter rates, and swimming speeds.

For this topic, we have endorsed the proposed Endurance lines off the west coast of the United States (Figure F-3). We will need to go beyond the scope of coastal currents to define the edges of grazer population boundaries, and suggest that

Figure F-3. The Endurance line concept is based on the recognition that climatic the identification of ecological responses to changes requires a large sample area (>10,000 square kilometers) and an extended deployment time lines (>10 years). Illustrated here is an array of Endurance lines along the western coast of North America. The series of cross-shore lines would provide sustained measurements supporting local studies of the continental shelves while also providing comprehensive arrays to study western boundary ecosystems. It is very conceivable that all of these lines may be deployed at the same time, in the same location. The array of Endurance lines provide the scientific justification for a Pioneer array deployment, which in turn triggers a RAPTOR deployment. Alternatively, an event on the Endurance lines may trigger its own RAPTOR deployment.

there should be at least one permanent open-ocean facility in each gyre, hence, there should be another one added to the eastern North Pacific between California and Hawaii. On the West Coast, we envisage two coupled regional studies north and south of the Juan de Fuca plate. The southern study would run from Baja California north to the Juan de Fuca plate, and the other northern regional study from the Juan de Fuca plate north through the Gulf of Alaska. The North Pacific regional array provides the opportunity to make measurements at the boundary between these proposed southern and northern regional programs. In addition, autonomous systems could be continuously deployed between the lines to fill in key spatial and temporal information. We will still require shipboard studies within these regions for process studies. These process-oriented cruises will provide the more-exact measurements of metabolic rates and processes, which will be used to calibrate and validate those on the autonomous platforms. In addition, we will need to connect the observatory programs with other ongoing ocean sampling programs, for example, NMFS fisheries cruises, and augment the food web studies with other data streams that may provide closure between the abundances and processes sampled along these Endurance lines.

The backbone core suite of sensors should be deployed as early as possible. Process studies could then be designed to build upon existing observational programs. These process studies are needed to help in the interpretation of data from the new process-oriented sensor systems (e.g., 3-D acoustics). Sensor development for process studies would provide near-term (<5 years) successes. Decadal data streams from moored and autonomous sensor arrays would provide the long-term information (>20 years) to finally begin to address regime shifts and their reversibility. Data from these systems will provide new results about the oceans and also help us understand the possibilities and limitations of the new sensors. Over a full deployment cycle of 20 years or more, we could tackle the question of the PDO response in food webs from Baja California to Prince William Sound.

How Do We Entrain the Scientific Community?

Effective observatories require the participation of many groups of collaborators. This ORION-scale effort will need to be more collaborative than any past effort, as it will require reliance on similar data streams collected by multiple investigators to piece together the larger temporal- and spatial-scale information composites. Trust will be at a premium, so there must be transparency in the infrastructure, data streams, and funding efforts. In addition, we see a need for an increase in education infrastructure to supply the large pool of Masters-qualified science and technical support that will be required to implement this program.

A couple of concerns were continually voiced. The four top-ranked concerns: (1) recognize that required funding levels are quite large for just the food-web component, and that there are many other discussion groups probably asking for similar resources, (2) the long-term commitment (>20 years) of such funding levels for infrastructure and community assets has only been seen at the ship level, (3) there are not enough qualified people to develop and deploy these systems, as well as to analyze the voluminous data streams these systems would produce, and (4) the need for transparency and trust within the research and implementation community. ORION program leaders are asking for a tremendous amount of community support for a project that appears underfunded and dedicated to other ventures. Convincing the greater oceanographic community that the ORION program is in the best interest of all will be a major task for the ORION steering committee. Despite these concerns, this group believes in the potential of ORION to develop paradigm-shifting science from the significant investment in infrastructure, and to resolve temporal and spatial aliasing in grazer population and process sampling.

IN SHORT – FUND IT, DEPLOY IT, AND COMMIT TO IT.

Food Webs Working Group

- James Ammerman, Rutgers University
- W. Paul Bissett, Florida Environmental Research Institute
- Lisa Campbell, Texas A&M University
- Steven Conway, Texas A&M University at Galveston
- Kendra Daly, University of South Florida
- Brad De Young, Memorial University of Newfoundland
- Percy L. Donaghay, University of Rhode Island
- Sharon Franks, Scripps Institution of Oceanography
- Scott Gallager, Woods Hole Oceanographic Institution
- Ralf Goericke, Scripps Institution of Oceanography
- Bob McLure, Biosonics, Inc.
- Dave Musgrave, University of Alaska
- Ray Smith, University of California, Santa Barbara
- Jennifer Trask, Monterey Bay Aquarium Research Institute

G. Human Impacts on Marine Ecosystems

Michael Bruno (Moderator), Mark Luther (Rapporteur)

Perhaps more than any other issue facing the scientific community, the assessment of human impacts on marine ecosystems requires the wide range of temporal and spatial observations that can only be accomplished with an ORION infrastructure. For example, alteration of biogeochemical cycles as a result of human activity is potentially changing which nutrient limits primary productivity in the coastal ocean and is potentially altering which planktonic species dominates the ecosystem. If left unchecked, these changes will likely have significant, permanent impacts on coastal water quality, fisheries, and human health.

To understand and predict long-term responses of an ecosystem to both gradual and episodic (e.g., storm, oil spills) human-derived material fluxes and their concomitant biogeochemical impacts requires temporal and spatial coverage of decades and hundreds of kilometers, respectively. To understand and assess direct biogeochemical impacts of human-derived materials (e.g., nutrients, pollutants) on local ecosystem processes requires temporal and spatial resolutions of seconds and centimeters, respectively. Determining the physical fate of agents introduced by humans also requires large-scale observational capabilities that can capture the transformation of material as it is being advected.

Scientific Priorities

1. Determine the extent to which human activity is altering oceanic ecosystems.
2. Determine how long it takes for marine ecosystems to recover from various human-induced changes.
3. Determine the circumstances by which human-induced changes can lead to regime shifts where the system cannot return to its previous dynamic equilibrium.
4. Evaluate the extent to which human-induced changes in the oceanic ecosystem impact human societies.

The ORION infrastructure will provide sufficient power and bandwidth to support key sensors for focused experiments covering the entire range of natural and anthropogenic influences on coastal ecosystems. Data collected over broad regions at very high sampling rates will allow focused study of multiple ecosystems, each with distinct characteristics and compelling scientific, societal, and educational issues. ORION will also encourage small research communities and individual investigators to leverage technical expertise, new observations, and data-dissemination methods that are not practically available otherwise.

Example ORION Experiments

The "Human Impacts" working group focused on three coastal ecosystem types to study: coral reefs, the zone where large river systems meet the ocean, and urbanized estuaries. Specific sites were chosen in part based on their potential to leverage existing observatory capabilities of the National Marine Sanctuary program, the National Estuary Program, the National Undersea Research Program, and the National Estuarine Research Reserve (NERR) program, among others.

Studies of human impacts will be carried out by collecting measurements of temperature, salinity, directional waves spectra, nutrient concentrations (ideally both oxidized, reduced, and organic nutrient sources), oxygen concentrations, carbon budgets, growth rates, and pH. These measurements should be collected in a range of ecosystems that are experiencing different human-induced stresses. This would allow for focused time series but also allow comparison studies of the impact of human activity on the oceans.

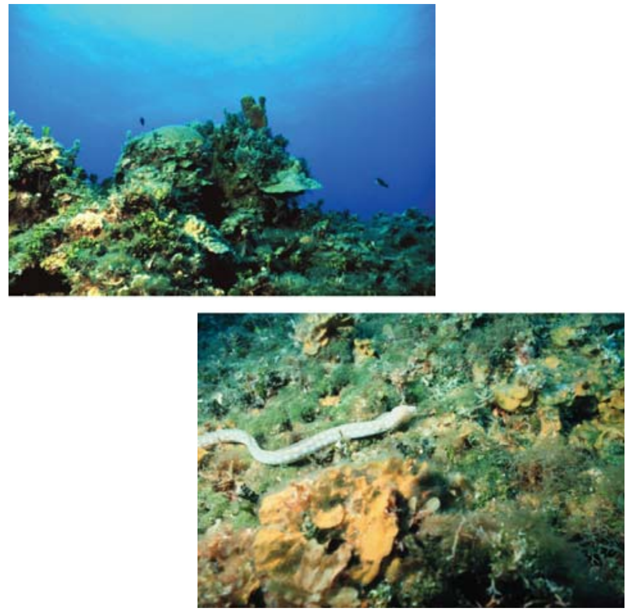


Figure G-1. Two examples of algae overgrowth in Discovery Bay. Photos taken by Christopher Moses, University of Miami.

What levels of anthropogenic inputs can coral reefs tolerate before shifting to algal dominance?

Coral reefs are among the most diverse and productive ecosystems on Earth. Although they can exist in apparently oligotrophic environments, there is growing recognition that corals reefs are facing a global decline in health from anthropogenic influences. These influences, such as increased fishing, exploitation, and pollution, are particularly manifest in the Caribbean, and are causing a shift from coral to algal dominance (Figure G-1). A number of additional, more-subtle factors are likely contributing to coral reef decline, including delivery of toxic materials (e.g., heavy metals and biochemical compounds [pesticides]), enhanced nutrient runoff, and pathogens carried through rivers and groundwater. Enhanced atmospheric deposition of wind-borne dust, changes in the composition of the atmosphere (principally CO_2), and the consequent influence of CO_2 and other greenhouse gases on sea surface temperatures and pH also affect the health of coral reef ecosystems. In particular, the precise effects of this latter group need to be identified and ameliorated.

As a first step in understanding the various factors that can contribute to coral reefs' decline, a basic understanding of carbon and nutrient flow paths in healthy coral reefs needs to be established. Such information is currently absent because measurements of critical parameters affecting coral reefs such as dissolved oxygen concentration, and organic and inorganic nutrients, are only made quarterly, and in limited areas, which is known to be insufficient to capture the much greater temporal and spatial variability that exists due to local weather and tidal flushing.

Initially, a variety of sensors installed along major portions of a healthy reef (many tens of kilometers) and along transects at right angles to the reef margin will continuously record the environmental and reef variability over many years. Ideally, more than one healthy reef would be monitored at one time. Instrumentation would include nutrient sensors (nitrate, nitrite, ammonia, phosphate, optical sensors measuring pelagic algae and colored dissolved organic carbon [CDOM]), *in situ* sensors for metal concentration and bulk dissolved organic carbon and dissolved oxygen, pH meters, dissolved CO_2 sensors, spectral radiometers, and CTDs. All of the above sensors should be able to sample at very high frequency (order of minutes), at high spatial resolution (order of centimeters), and with sensor spacing on the order of meters. Sensors will also be installed to provide measurements throughout the water column and at the sea surface.

Data collected within the reef and in the water column will provide the needed quantitative information about nutrient flow paths into and out of the reef, but also within the living reef itself. Changes in nutrient delivery patterns will be correlated to coral health and productivity via fast-repetition-rate fluorometry and oxygen evolution. The long-term records of nutrient flow paths will then be used to assess the relative significance of atmosphere, groundwater, agricultural runoff, and coastal upwelling nutrient delivery to the reef's long-term health. Note that this data resolution will permit studies of the very rapid (hours) ecosystem "phase shift" from coral to pelagic algae that may occur because of short-term, subtle changes in nutrient inputs.

Long-term changes in reef diversity and the associated biological communities could be captured via video and correlated with nutrient input patterns. Such spatial time series will be particularly important for quantifying the importance of mesoscale processes, such as upwelling, on the diversity and health of the reef. Mesoscale processes have never been adequately studied in the past due to limitations in sampling the appropriate spatial scales. Individual investigators might complement the standard core measurements by deploying biochemical-genomic sensors to measure coral bleaching rates and disease, and *in situ* mass spectrometers to measure elemental concentrations (Fe, Cu) and airborne materials (Fe, pathogens). Candidate locations for a coral reef observatory include tropical and temperate coral reefs in the Florida Keys, Puerto Rico, Virgin Islands, the Caribbean Islands, Texas, and the Hawaiian Islands.

How do human activities that alter the chemistry of large river systems affect hypoxia in coastal ocean ecosystems?

Concentrations of nitrate in rivers and the consequent nitrate load to coastal areas in the United States have dramatically increased in the last few decades. For example, the nitrate concentration in the Mississippi River has doubled since the 1950s and the silicate concentration has declined by half (Rabalais et al., 1996). Total phosphorus (P) loads have decreased in many areas of the country, due at least in part to increased point-source control (Smith et al., 1987). As a result of these changes, the ratios of nitrogen (N), phosphorus, and silica (Si) in the Mississippi River are now more in balance and very close to the Redfield ratio (C:N:P = 106:16:1) (Redfield, 1934; Falkowski and Davis, 2004; Justic et al., 1995; Justic et al., 2003; Rabalais, 1996). As part of this trend, the N/P ratio in the river has increased to Redfield levels, and the N/P ratio in the northern Gulf of Mexico now exceeds Redfield levels (Rabalais et al., 1996), increasing the likelihood of P limitation. This has also increased the potential for Si limitation (Justic et al., 1995). The implications for such large changes in nutrients' budgets of rivers and the subsequent impact on coastal ecosystems remains an active area of research. Although the enhanced algal productivity of some large rivers has been hypothesized to underlie the growing hypoxia in coastal ocean ecosystems (Figure G-2), the sequence of events has yet to be demonstrated because ship-monitoring efforts cannot maintain a sustained seasonal spatial presence.

To understand the impact of enhanced nutrient input and subsequent export flux on hypoxia in coastal ecosystems requires collecting sustained spatial time series from the river's mouth out onto the continental shelf. The mesoscale spatial arrays need to be oriented both along-shore and across-shore to capture the meandering plume of river water as it flows out onto the continental shelf. The observational array should have higher horizontal and vertical resolution near the river's mouth than on the shelf. Because the inter-annual variability of river systems is large, the observatory should be maintained long enough to capture both low and high outflow years. The time-series measurements of such an observatory should include river hydrodynamics, temperature, salinity, macro and micro nutrient concentrations, oxygen and

Box 7. Lagrangian Transport and Transformation Experiment (LaTTE) Public Outreach Efforts

Contributed by Janice McDonnell, Rutgers University

In spring 2004, Rutgers University spearheaded LaTTE (Lagrangian Transport and Transformation Experiment), a five-year research project funded by the National Science Foundation to study the transport of nutrients from an estuary (New York/New Jersey) into the coastal ocean. Collaborating scientists from Lamont-Doherty Earth Observatory, University of Massachusetts, Florida Environmental Research Institution, California PolyTechnic State University, and the University of Florida used data streams generated by Rutgers, Stevens Institute of Technology, the National Oceanic and Atmospheric Administration, and the National Weather Service and applied the data to dye experiments to examine processes that control the fate and transport of nutrients and chemical contaminants in the Hudson River plume. Urban estuarine plumes serve as an on-ramp for the transport of nutrients and chemical contaminants to the coastal ocean.

In an effort to inform the public of the important experiment, educational outreach efforts were started that will continue through the balance of the project. An information web site about the project was created so that interested parties and press could be directed to accurate information about the project. Classroom lesson plans and tools are currently being created to coordinate with future runs of the experiment. And, a tremendously successful full-page newspaper advertisement was submitted (see figure and http://marine.rutgers.edu/cool/latte/pressroom/pdf/GannetDailyNewspapers_RutgersScience.pdf). The page was an engaging way to inform the public about the science behind the project and what the scientists hope to achieve. The Rutgers science pages have won several awards and have increased the amount of general web traffic. The LaTTE page was also translated into Spanish to reach a target population of substance fishers in the region, and to engage the Latino community.

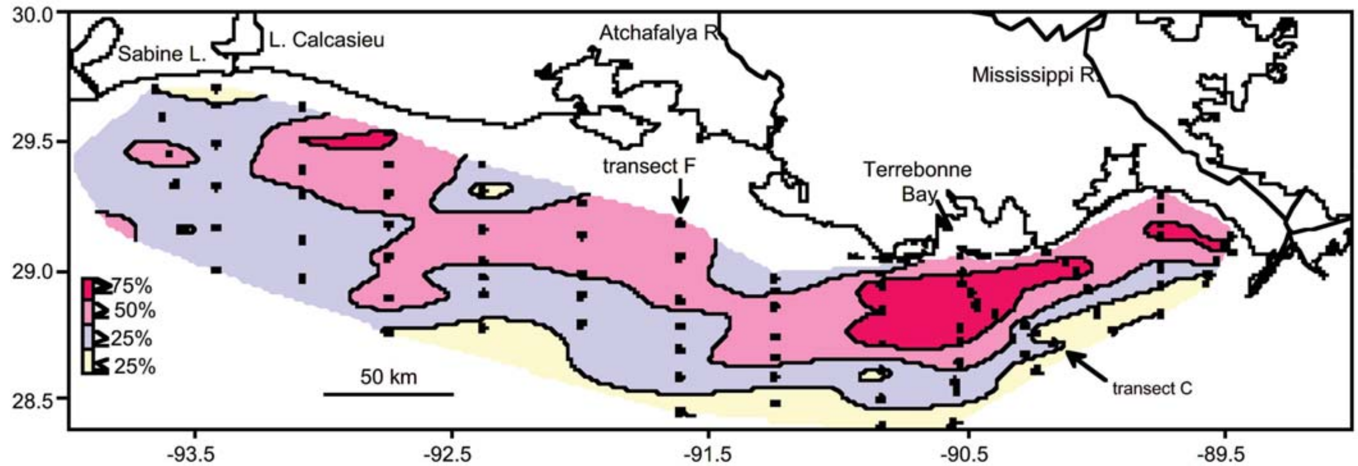


Figure G-2. Frequency of bottom-water hypoxia (dissolved oxygen less than 2 mg/l) for mid-July 1985-2002 in the Gulf of Mexico. Figure modified from Rabalais et al. (2002).

carbon concentrations, and inherent spectral optical properties. Candidate systems include the Mississippi River delta, the Columbia River littoral cell, San Francisco Bay, and the Sacramento and San Joaquin Rivers.

How does urbanization alter chemical and biological cycling rates in estuaries and coastal ocean ecosystems?

Urbanization can profoundly influence the biology and chemistry of inland and coastal waters (Figure G-3). Impacts include increased point and non-point macro and micro nutrient loading, heavy metal and chemical contamination, dredging, dredge disposal, and enhanced water runoff. Additionally, estuaries and adjacent coastal zones are often subject to heavy fishing pressures and boat traffic. The complexity of these systems is increased by the relatively high turbulence of the water, which directly influences the transport and fate of chemical constituents. For example, urban estuarine buoyant plumes represent a major pathway for the transport of nutrients and chemical contaminants to the coastal ocean. However, the fate and transport of this material is controlled not only by the dynamics of the plume but also by biological and chemical processes that are coupled to the dynamics of the plume. A vertically thin plume during upwelling conditions will have enhanced light levels that will promote biological production and will potentially increase the rate at which chemical contaminants enter the food chain. Additionally, sediment trapping, re-engineering of channels, and the interannual variability in precipitation and flow is significantly altering river flow patterns and rates. In the extreme, this alteration is eroding wetlands on the Gulf coast of Louisiana at a rate of one football field every 40 minutes. How these erosion rates enhance or retard elemental and biological rate processes is unknown.

To understand how urbanization affects estuarine ecosystems, sensors must be placed in key regions of the estuary, with a denser number of sensors nearshore. For urbanized estuaries, measurements are required at 1-cm intervals in the water column to adequately define turbulence levels and mixing rates, and to document the presence or absence of microlayers both at the surface and in the water column itself. These layers can contain contaminants deposited from the atmosphere and rivers. The full ORION estuarine sensor network will provide information on mesoscale hydrography, particulate and dissolved material concentrations, and macro- and micro-nutrient concentrations. Given these requirements, time-series measurements will include those for currents, waves, stratification, temperature, salinity, wave transformation, suspended sediment characteristics, and transport (cohesive and non-cohesive), bottom boundary layer thickness, dissolved oxygen freshwater inflow, nutrient concentrations, and fish biomass. Measurements of the higher ecosystem trophic levels will be a key measurement

Figure G-3. The Passaic River at Newark, New Jersey, a tributary of the heavily urbanized Hudson-Raritan Estuary. Photo by Michael Bruno, Stevens Institute of Technology.

for these efforts to permit assessment of whether elemental mobilization resulting from enhanced sediment resuspension is biomagnified in the higher trophic levels. These standard time-series measurements could be made using off-the-shelf CTDs, acoustic Doppler velocimeters (ADVs), and bio-optical and acoustic sensors. These sensor arrays should span the source location(s) inside the estuary to the open ocean (sink). Measurements could be augmented by individual projects focused on fish migration, erosion/wetland and shoreline loss, sediment budget (including armoring and channelization) larval transport, and non-native and invasive species. Measurements that might be made by individual investigators using the ORION network might include levels of contaminants, pathogens, and pharmaceuticals. Potential locations where urbanized impacts can be monitored and assessed include the Hudson-Raritan Estuary, the Chesapeake Bay, and Puget Sound.

Long-Term Challenges for ORION

Long-term hurdles for ORION are related to the development of robust sensors that measure critical environmental parameters. For example, there is a need to develop robust profiling technologies that will provide the full nutrient profile, oxygen, pH, and carbon measurements with adequate spatial (centimeters) and temporal (seconds) coverage and long-term stability. The development of new sensors and techniques for defining suspended-sediment characteristics and concentration in heterogeneous cohesive and non-cohesive environments may occur through a mix of acoustics and hyperspectral optics. Additionally, robust methods for measuring the deposition of airborne materials (both particulate and dissolved) need to be developed.

Box 8. Mysteries of the Coastal Dead Zones

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

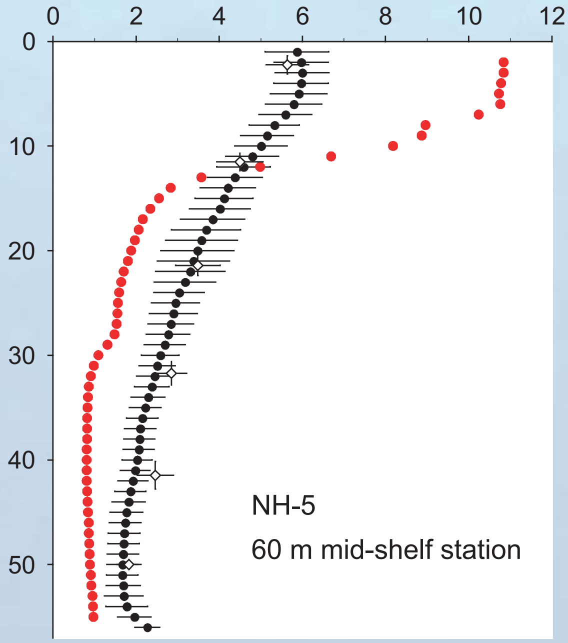
The upper 100 m of the water column is home to the majority of the ocean's biological activity. This activity is stimulated by the availability of both nutrients and the light required for photosynthesis. Very often, upper ocean nutrient availability limits phytoplankton growth, and so most activity tends to be concentrated at special times or places. Further, the ocean ecosystem has evolved in balance with the distributions of food and dissolved oxygen. Changes in that balance, whether forced by climate variability, both natural and anthropogenic, or excessive nutrient input from land runoff, can lead to the depletion of oxygen resulting in die-offs in microbes, fish, shell fish, and invertebrates. Although the human-induced causes of low dissolved oxygen (DO) have recently received much attention, low-frequency natural cycles in the oceans are significant and are the likely culprits driving past basin-scale ocean anoxic events. The sequence of events that underlies patterns of low DO zones in the modern ocean is unclear as human-induced changes are increasing and confounding the natural forcing of hypoxia/anoxia. Although the dead zone in the Gulf of Mexcio is well documented, other regions around the country are also experiencing dead zones.

West Coast of the United States: In summer of 2002, an unprecedented development of severe inner-shelf (<70 m) hypoxia (dissolved oxygen levels less than 1.43 ml/l) and resultant mass die-offs of fish (figure, bottom) and invertebrates occurred within the northern California Current System (Grantham et al., 2004). Low oxygen levels were observed and covered at least 820 km^2 off central Oregon and persisted for over two months. In the middle of this region, crab mortality in commercial crab pots was over 75%. The massive die-offs were attributed to low values of DO in the lower half of the water column, values far less than the historical summertime average (figure, right). The cause of the low-oxygen bottom water was traced to the anomalous southward transport of cold, fresh, nutrient-rich subarctic water into the northern California Current (Freeland et al., 2003; Wheeler et al., 2004). Thus, the source waters for upwelling were not only low in oxygen, but also supplied anomalously high levels of nutrients to the euphotic zone over the continental shelf. This fueled coastal phytoplankton blooms that, upon sinking to the ocean bottom, underwent respiration and contributed to the further drawdown of oxygen. Massive invertebrate die-offs were observed again off central Oregon in summer 2004 and, as in 2002, the cause was hypoxic bottom water. This time, though, the upwelling source water properties were not anomalous (i.e. the anomalous southward transport of subarctic water had diminished). This points to the greater role of increased phytoplankton production off central Oregon (a two- to four-fold increase observed since 1998) and subsequent sinking and consumption of oxygen. Another piece of the puzzle is the influence of wind forcing in the 2 to 10 day "weather band." The degree to which the wind is steady or variable, influenced by larger

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 from Grantham et al., 2004.

time- and space-scale ocean-atmosphere interactions, plays a role in how low-oxygen water is flushed away from sensitive habitats and in maintaining or dispersing concentrated surface phytoplankton blooms.

The details of ocean-atmosphere interactions that lead to increased transport of subarctic water into the northern California Current and the subsequent coastal ecosystem response are still unknown and can't be sorted out without better observations and understanding of the coupled physical, chemical, and biological dynamics. Multiparameter moorings placed in key areas would pin down the characteristics of upwelled source waters. High-spatial-resolution moored arrays capable of profiling the entire water column over the continental shelf would establish the coupled physical-chemical-biological processes in these episodic hypoxia events. Deep-sea buoys placed in the high-latitude North Pacific equipped to measure air-sea fluxes, coupled with ocean and atmosphere circulation models, would allow understanding and ultimately predictive capability for how climate variability leads to anomalous transport of water masses within the ocean interior and ultimately how they supply water properties to the productive continental shelves.



Dissolved oxygen profiles for July 2002 (red) compared with recent values (1998-2001, black circles) and historical averages (1960-69, 1972, open circles) five nautical miles off the Oregon coast at 44.65°N. Figure from Grantham et al., 2004.

East Coast of the United States: Widespread, recurring but variable hypoxic conditions are also observed in the Mid-Atlantic Bight (MAB). For example, in 1976, a major hypoxic event impacted nearly the entire New Jersey continental shelf, resulting in over $550 million in losses to the shellfishing and related industries (Figley et al., 1979). Initially, anthropogenic nutrient releases were blamed for the development of the hypoxia. More recent data suggest that interactions between seafloor topography and summer upwelling might underlie the low DO along the New Jersey shore (Glenn and Schofield, 2003; Glenn et al., 2004). Upwelling along New Jersey is a complex interaction of atmospheric forcing, bottom topography, and local and mesoscale circulation. Although upwelling and oxygen depletion appear to be spatially linked, the sequence of events that drives the intensity of upwelling and corresponding recurrent low DO zones is unclear and requires a regional perspective. This is especially important as human-induced changes are increasing and will likely confound the natural forcing of MAB hypoxia.

To overcome the undersampling problem, a coupled modeling and observation approach is required. Real-time observations made with moorings, cabled observatories, and mobile assets will provide the spatial perspective on the hypoxia anoxia. The time-series sites could provide data that would be impacted by both topographically driven circulation patterns and the increased nutrient loading associated with urbanized rivers and water sheds. This observational strategy would allow scientists to collect data throughout the year even during strong storms. The wealth of information will provide the means to initialize and validate coupled biogeochemical models and enable efforts to isolate the effects of naturally topographically driven hypoxia/anoxia from that associated with human activity.

Entraining the International Community

The Human Impacts working group thought that many of the scientific issues raised during the meeting would provide an ideal suite of scientific questions that could be used to foster international collaboration through comparative projects. Some of the specific international efforts that could be pursued include the global degradation of coral reefs (partner with Australia, other western Pacific nations), a Cuba-Florida regional array (similar natural forcing in both locations, but significantly different anthropogenic influences), and the lessons learned from the Mississippi River and the Three Gorges Dam (China).

Entraining the Scientific Community

Key ingredients that would entrain the wider scientific community for ORION projects were discussed. The importance of having core data freely available to all scientists in real-time was viewed as particularly critical to ORION's success, and requires the standard proprietary nature of science research to evolve. Outreach might be facilitated through providing mechanisms where scientists not familiar with ORION can get assistance in preparing proposals. Finally, there is a need to minimize the divide between the applied (served by the IOOS) and theoretical science communities so that useful data products can be developed.

Human Impacts Working Group

- Michael Bruno, Stevens Institute of Technology
- Margaret Davidson, NOAA Coastal Services Center
- Michael DeLuca, Rutgers University
- Norman Guinasso, Texas A&M University
- William Kirkwood, Monterey Bay Research Institute
- Mark Luther, University of South Florida
- Joan Oltman-Shay, Northwest Research Associates
- Judy Schoenberg, Girl Scouts of America Research
- Barbara Spector, University of South Florida
- Peter Swart, University of Miami
- Lauren Wetzell, University of South Florida

H. Ocean-Atmosphere Fluxes

Wade McGillis (Moderator), Jeff Nystuen (Rapporteur), Christopher Zappa (Rapporteur)

An improved knowledge of mechanisms underlying air-sea exchange is crucial to the interpretation of larger-scale biogeochemical and physical processes and feedbacks. An important contribution of ORION will be more-accurate input to models for air-sea fluxes that is founded on sound physical and biogeochemical principles. The large range of scales associated with the mechanics of air-sea exchange (from sub-millimeter to greater than 103 km) necessitates that such models be idealized. Accordingly, processes that have not been adequately resolved need to be parameterized. Unless these parameterizations are adequate and well founded, the models will have limited skill and predictive capacity with respect to climate and other environmental change. Such improvement requires quantitative measurements of the exchange (including wet and dry deposition) of mass (gases, aerosols, and water vapor), momentum, and energy (including heat) across the air-sea interface, as well as the biogeochemical and physical parameters that characterize the interface and drive the processes. These measurements are needed over long time scales (years) and from a wide variety of geographical regions and environmental regimes. Simultaneous intensive process studies of the physics and biogeochemistry of the air-sea interface will lead to improved understanding of the fluxes of momentum and energy and the interpretation of long-term, wide-spread measurements. Figure H-1 shows some of the processes and forcing mechanisms present at the ocean-atmosphere interface.

ORION's new observational framework will address model deficiencies across a range of scales—from shorter scales in coastal areas and near fronts to larger scales appropriate for global and climate studies. Air-sea fluxes need to be quantified to an accuracy within 10% over the relevant temporal and spatial scales depending on the application. Climate predictions, for example, are not justified until we get net air-sea fluxes at the appropriate accuracy. By providing long-term observations of air-sea interaction processes, ORION data will reduce statistical uncertainty and will uncover serious unknowns.

Scientific Priorities

1. Produce more-accurate maps of the global air-sea flux for carbon, momentum, heat, water, and aerosols and understand the pertinent temporal and spatial scales for both mean forcing and episodic events.
2. Identify unique regional features that contribute to air-sea fluxes. Develop an understanding of the dominant processes and their respective roles in these diverse regions.

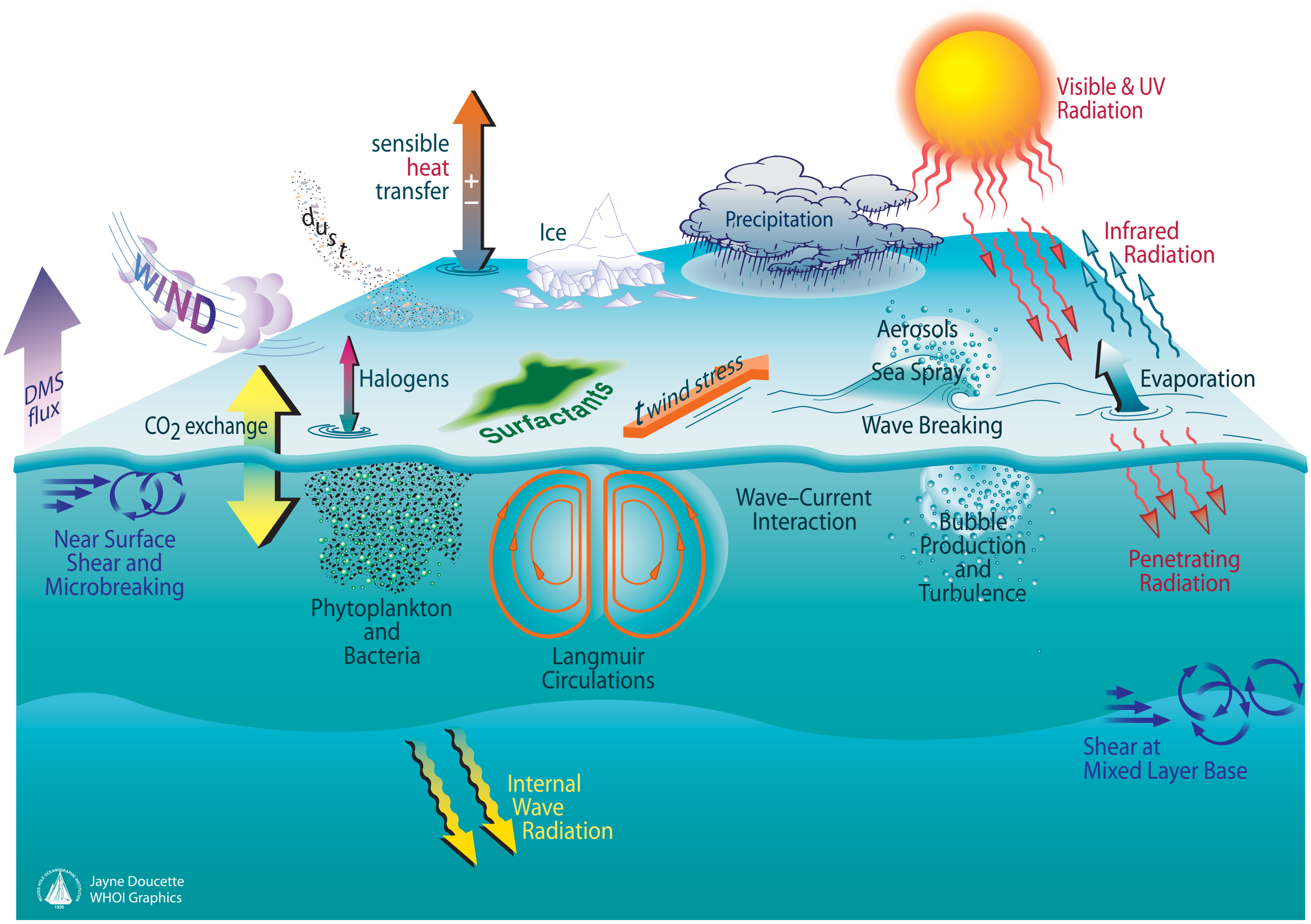


Figure H-1: Schematic of the air-sea interface with dominant processes and fluxes. ORION aims to significantly improve parameterization of air-sea exchange processes, thus allowing more-accurate estimations of regional and global flux fields, and their spatial and temporal variability.

ORION will also explore exciting regional hotspots that are important to our understanding of air-sea fluxes and will enable the next generation of experiments. These hotspot locations will also provide calibrated air-sea flux reference sites—30 have been determined necessary. Calibration of air-sea flux measurements is required using direct flux measurements at the flux reference sites. The reference-site network is designed to represent the distinct ocean-atmosphere regimes required to minimize the errors from global air-sea flux products.

The air-sea flux working group identified five exciting Air-Sea Flux Regions (Figure H-2) that would benefit from an ORION-based initiative and lead to transformational science:

1. The North Pacific Region would implement various ORION assets to target winter storm tracks with high-wind-speed situations as well as conditions where sub-surface subduction plays an important role.
2. Scientific objectives in Polar Regions include the study of coastal polynyas, tidal impacts on sea ice and lead formation, surface heat budget, and characteristics of ice-covered oceans. Coastal polynyas around the Antarctic continent produce much of the dense shelf water that ultimately feeds Antarctic Bottom Water (AABW) formation and thus affects both thermohaline circulation and the ventilation of the deep ocean. The remote location and episodic nature of the opening of coastal polynyas has been an impediment to the quantitative study of the atmospheric

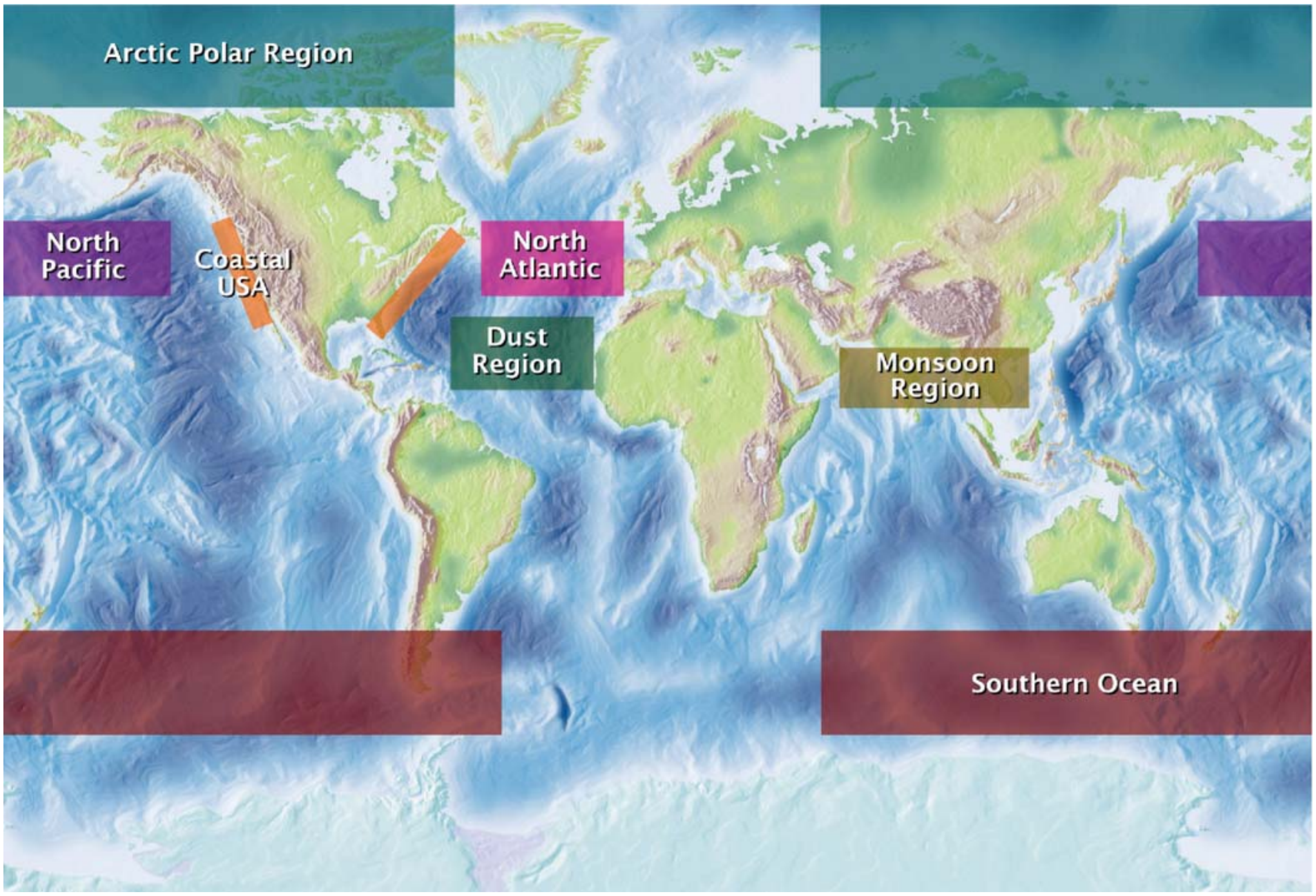


Figure H-2. Map of identified Ocean-Atmosphere Flux regions that would lead to transformational science and improve our knowledge of air-sea fluxes in a variety of environmental regimes.

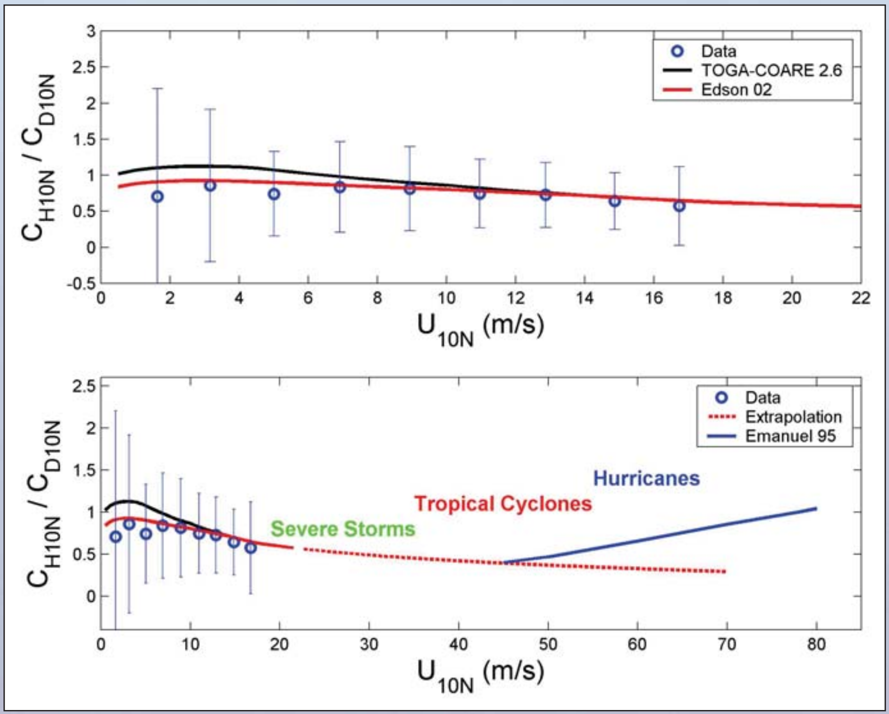
forcing by measurement of the air-sea-ice fluxes. ORION-based measurements from innovative platforms such as sub-surface moorings and sea gliders would greatly enhance the understanding of the processes of Antarctic polynya formation, their maintenance, and overall quantitative role in deep-water formation.

3. The Southern Ocean Region is a large unknown due to the difficult working environment and ORION is ideally suited to establish a presence in this region. Huge wave conditions are a unique component of air-sea interaction within this region due to the extreme winds and high waves. These conditions lead to an air-sea interface that is difficult to describe due to boundary layers of bubbles, foam, and sea spray. The region is thought to be an area of intense ventilation of the ocean boundary waters.
4. The Tropical Region is characterized by lower winds and strong insolation. Here, the water cycle (precipitation and evaporation) coupled with wind/radiative processes account for significant variability in the CO_2 flux and is compounded by different time scales of these physical processes.
5. Observatories along both North American coasts will allow for probing air/sea/land interactions in order to understand what really goes across an interface that is biochemically important in various geographical locations (e.g., rain events versus estuary flows versus runoff). Coastal models will require algorithm variability where patterns of wet and dry deposition are almost unknown. Coastal observatories engender high public interest due to the human impact and outreach opportunities.

Box 9. Winds at Sea: What Do We Really Know?

Contributed by James Edson, University of Connecticut

In the last few decades, substantial progress has been made in our ability to make direct measurements of momentum, mass, and heat fluxes 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 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 the exchange of heat, mass (water vapor, gases, and liquid water in the form of sea-spray), and momentum at wind speeds above 20 m/s. Additionally, large uncertainties remain in the fluxes of heat and mass at nearly all wind speeds. This is illustrated in the figure below, which 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 little information about air-sea exchange in severe storms and no direct surface-layer measurements in tropical storms and hurricanes. The figure also illustrates the large uncertainties still exist below 20 m/s, primarily due to the difficulties associated with measuring the scalar coefficients (heat in this case). This represents a real impediment to accurately forecasting storm intensity, the surface wave field, the evolution of the upper ocean, the feedback between the two boundary layers, and, ultimately, climate change. In fact, numerical modelers have shown that extrapolation of current parameterizations (the broken red line) do not allow the formation of hurricanes due to too much drag and/or too little fuel exchange, and have proposed parameterizations like that shown in blue. Therefore, we also

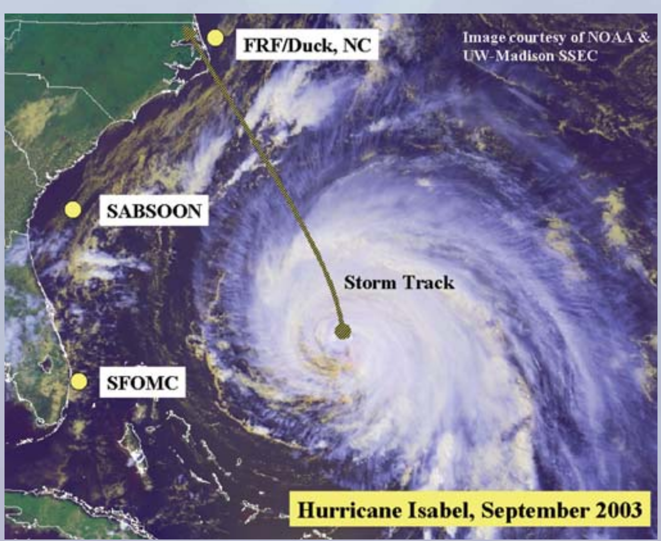


Relationship between the ratio of the heat to momentum exchange coefficients (y-axis) versus wind speed (x-axis). Points show where measurements have been made; lines represent extrapolations made for models. Note how few data exist for extreme storm events.

have to greatly improve our models of fluxes at high wind speeds and to recognize that the use of simple bulk formula and averaged atmospheric and oceanic variables under these conditions is likely to be insufficient.

Our inability to make these measurements at high wind speed is due to the harsh conditions encountered at sea, and also because research vessels do not willingly enter into these regions due to safety concerns for the crew and scientists. 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 coastal observatories and on ocean moorings. Some of these need to be arranged along probable storm tracks (existing observatories that meet the location criterion are shown in the figure) or by deploying arrays in oceans associated with high wind. The latest generation of sonic anemometers is capable of providing accurate estimates of momentum and buoyancy flux to wind speeds of 30 m/s.

Extremely rugged, fast-response anemometers must be developed to survive extreme wind conditions encountered in hurricanes and typhoons. A number of reliable instruments are now available to measure heat and moisture fluxes; however, rugged thermometers and hygrometers must be developed to handle the high winds and spray. The same is true for sensors that can accurately measure the flux of spray itself and gases such as CO_2; however, these sensors are more prototypical and require substantial development efforts to provide long-term, autonomous measurements. Similar challenges exist at the ocean surface and within the ocean mixed layer where sensors or sensor system capable of measuring, for example, the directional wave field, bubble size distributions, and near subsurface structure in severe conditions are required. A number of promising systems for these types of measurements exist (e.g., profiling drifters for the upper ocean and aircraft-based remote-sensing systems for the wave field), but all require additional development efforts for operational use. All of these developments will greatly increase understanding of marine storms, ocean waves, upper ocean circulation, climate change and their impact on the physics, chemistry, and biology of the oceans, and will require a dedicated effort within the context of ORION.



The location of three existing ocean observatories superimposed on a satellite image of hurricane Isabel: the U.S. Army Corps of Engineers Field Research Facility (FRF), the South Atlantic Bight Synoptic Offshore Observatory Network (SABSOON), and the South Florida Ocean Measurement Center (SFOMC). The image also shown the storm track of Isabel's eye, which made landfall almost directly over the FRF on September 18, 2003. While these observatories continuously measure a wide variety of oceanographic and atmospheric variables, they were not equipped to make direct measurements of momentum, heat and mass fluxes during the passage of Isabel.

In addition to the five Geographical Regions, we identified three Environmental Regimes:

1. Convectively Driven Regime where wind plays a diminished role and the air-sea fluxes are strongly coupled to radiation and precipitation.
2. Wind-Driven Regime where the wind dominates and generates a coupled response to wind waves and currents.
3. High-Energy Regime where a coupled response exists under extremely high wind conditions with a "blurring" of the air-sea interface (e.g., bubble/foam/sea-spray layers). This High-Energy Regime is identified as a top priority. A new paradigm must be addressed for this situation because present flux methods are totally inadequate. At present, we are not even able to get the order of magnitude correct for hurricanes.

Contributions of ORION to Ocean-Atmosphere Fluxes

... Provide a local climatology for intensive, short-duration field campaigns.

... Further facilitate regional studies of coastal processes by providing infrastructure that supports easy access to electrical power and data.

... Provide a reliable system of rugged sensors that allow opportunistic sampling of extreme events.

... Provide continuous, long-term (25-30 years) observations for climate studies.

... Provide a flexible system capable of supporting a wide range of instrumentation and platforms, such as AUV docking stations.

... Provide a means for public outreach and educational programs.

... Contribute to a larger network of observatories and platforms for real-time observations that can help verify and improve ocean and atmosphere models.

Example ORION Experiments

High Wind Air-Sea Flux Platform Experiment: The High-Energy Regime was targeted as a priority because little is known about air-sea fluxes above wind speeds of 20 m/s. High-wind events comprise a high percentage of the global energy budget. Parameterizations of air-sea fluxes break down when the interface is poorly defined. We need to quantify the drop and bubble size distributions and their influence on the air-sea flux because spray and bubbles/foam characterize the fuzzy interface. We need to develop a new framework for new algorithms. An understanding of these processes is necessary for climate modeling and prediction. Process studies have not been able to catch the episodic high-wind-speed events. Long-term time series will provide the capability to perform sustained studies that will catch these events. As current technology cannot operate in these extreme conditions, new capabilities are needed to gather both the long-term mean data and to accurately measure high-intensity episodic events.

Coastal Experiment: Land/Sea/Air processes have many human impacts, a few of which are outlined in the outreach section. Coastal observatories such as the Martha's Vineyard Coastal Observatory (MCVO) (see Figure H-3 and http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi) are perfect complements to ORION. Observatories such as MVCO are able to withstand the harsh elements through various seasons as well as strong episodic events such as winter storms or hurricanes. This platform survivability allows for long-term studies. Coastal observatories also are excellent areas to determine necessary instrumentation and to test instrumentation. An example of a coastal study is the effect of air-sea heat flux on biology and its feedback mechanisms on the coastal carbon cycle. This example combines offshore, benthic, and atmospheric exchange and includes special requirements for coastal observatories such as sediment transport, lateral transport from land (vertical from land with air-sea deposition), direct anthropogenic input (e.g., pollution, activity), reactive gases (O_3, NO), and elevated surfactant.

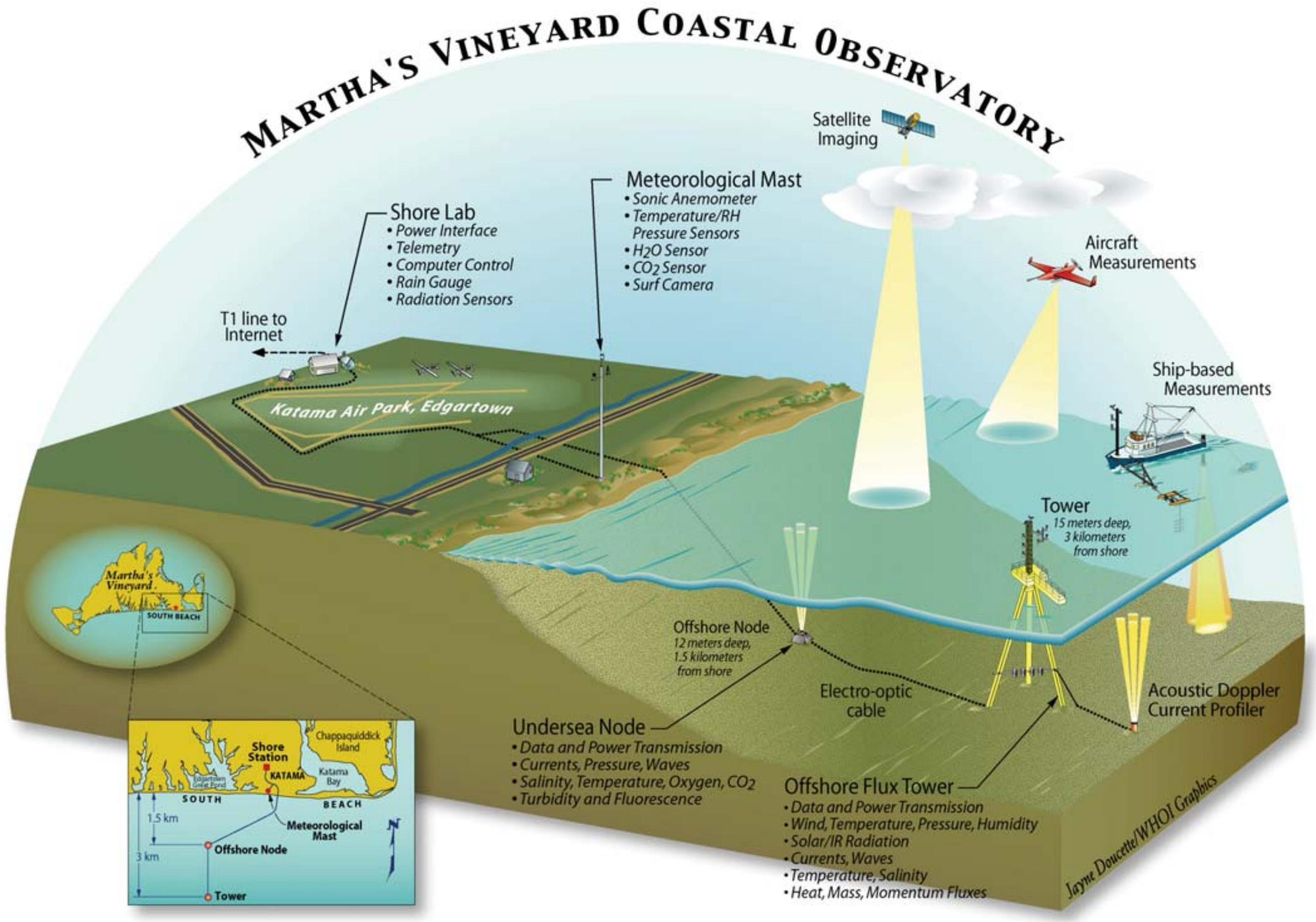


Figure H-3. Martha's Vineyard Coastal Observatory (http://mvcodata.whoi.edu/cgi-bin/mvco/mvco.cgi). MVCO is currently a fully operational coastal observatory with continuous oceanic and atmospheric measurements. The MVCO includes a small shore lab located between the hangars at Katama Air Park, a 10-m meteorological mast near the South Beach Donnelly House, a subsurface node mounted in 12-m water depth approximately 1.5 km south of Edgartown Great Pond, and an air-sea interaction tower (ASIT) equipped with a top-side node to allow access to air-side or underwater instrumentation at the 15-m isobath. The core set of instruments at the meteorological mast measure wind speed and direction, temperature, humidity, precipitation, CO_2, solar and infrared radiation, momentum, heat, and moisture fluxes. The core oceanographic sensors at the 12-m offshore node measure current profiles, waves, temperature, salinity, and near-bottom wave-orbital and low frequency currents.

Optically important constituents (OICs—such as phytoplanckton, non-algal particles, CDOM) cause depth-dependent absorption of solar radiation especially in coastal waters. Phytoplankton has been shown to significantly affect the radiative heating on mixed-layer depth scales in the deep-ocean (Siegel et al., 1995) and heating variability associated with chlorophyll has been modeled by Olman and Siegel (2000) and Ohlmann et al. (2000a). To date, little or no work has been done to examine the effects of OIC to the heat budget in coastal waters.

Measurement and modeling of the variance of the heat budget must include the effects of OIC, especially in the coastal zones, using instrumentation at ORION platforms. Heat input into the upper ocean is a combination of the absorption by these OIC (and their associated efficiency factors) and the turbid water. Synoptic heating estimates can be produced from OIC ocean color satellites with traditional radiative transfer models. A network of coastal observatories would extend the work *in situ* to synoptic and mesoscale processes.

Technological Advances

One of the key technological advances identified at the ORION workshop was the need for a re-locatable platform that could withstand high sea states and provide stability and survivability. Existing platforms such as *FLIP* have provided valuable measurements for over 40 years. *FLIP* is a unique 360-foot vessel that is towed to sea and literally flips up on end so that only the top 60 feet are above the water surface (Figure H-4). The result is a stable platform for housing scientists and their instruments that is ideal for making upper-ocean observations and atmospheric flux measurements at sea. Now is the time to develop the next generation of stable ocean-going platform. The time line for developing and implementing the platform is roughly five years, with five more years needed for sensor development. The expectation is to have an operational global flux observation program within 20 years. This type of platform would be used to develop understanding of sensor measurements from remote, unmanned moorings and buoys. It needs to be mobile so that it can be deployed at locations where unmanned moorings and buoys will ultimately be deployed to provide long-term operational data.

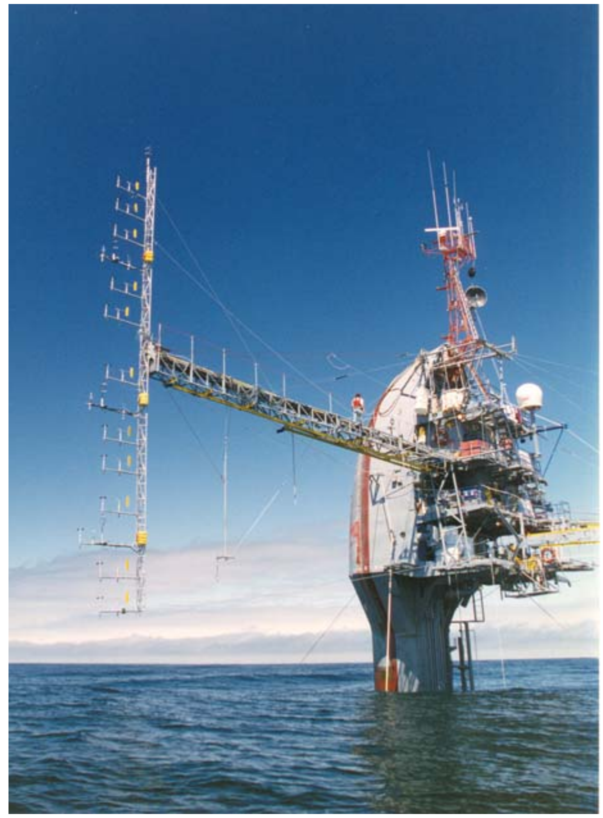


Figure H-4. Research platforms similar to *FLIP*, shown here, are necessary for the next generation of transformational science in ocean-atmosphere fluxes. See http://www.sio.ucsd.edu/voyager/flip/ for mor information.

Acoustic measurements need to be made, including those using Acoustic Doppler Current Profilers (ADCPs) and side-scan sonars, and of ambient sound. For additional measurements, ORION needs to look into putting sensors on platform alternatives such as drifters, profilers ("Albatross" robotic bird), sea gliders, and submerged near-surface floats, but also the more traditional buoys, moorings, and ships of opportunity. This requires the development of sensors for moving platforms that could be less expensive than large, fixed-platform networks. Sub-surface moorings or lower-expression platforms would not interfere with the processes being measured.

To attain the goal of providing accurate and calibrated air-sea flux measurements at references sites, it is imperative to develop a new generation of robust chemical, biological, and physical sensors.

Outreach

The public wants to know more about severe weather, global warming, and ocean-borne hazards transmitted through the atmosphere (red tides, pollutants, aerosol-borne diseases). In particular, the coastal regions have great potential for ORION outreach, and can generate support for scientific work. Information in several areas would be useful to the coastal communities and the general public as well as coastal resource managers, emergency management agencies, and public health officials:

1. Hurricane tracking and intensity are important to:
   - Coastal resource managers
   - Emergency management agencies
   - Coastal communities
   - Recreational users (e.g., fisherman, boaters, surfers)

2. Water level and wave size are highly influenced by large storms that affect coastal erosion rates and damage property.
3. Wind transport of aerosols and microorganisms that influence the onset of red tides are important to public health officials. How do particles become airborne?
4. Long-term sea-level rise is a major concern of coastal zone managers, coastal planners, and developers.
5. Public understanding of the impact of the global carbon cycle on ocean health is an important education and outreach goal.
6. Airborne spread of diseases such as cholera is an important health problem.

The use of cyber-classroom technologies is an appropriate part of the coastal observatory and forms an important component for understanding physics, chemistry, and math at all levels of education. Examples of educational outreach are:

A. Long-term continuous stream data on air/sea flux in high wind conditions is important for classroom education in high school and in university teaching/research projects. Encourage classroom sponsorship of buoys so that they feel ownership and responsibility.
B. The use of exciting new technologies for sampling (such as unmanned aircraft, mechanical "bird" gliders or sea gliders) may increase awareness of the research in student populations as well as the general public.
C. Installing video and audio equipment to capture footage of extreme storm events may lead to the production of exciting special programs for the public. Such titles as "Eye of the Hurricane" or "Inside the Perfect Storm" were suggested for PBS, Weather Channel, or Discovery Channel programs.
D. Using our senses to experience science. For example, relating to gas exchange—the ocean smells—what is it and how does it get of the ocean and to your senses? The albatross has keen smell and can smell krill 10 km away—a great example of air/sea interaction. Another example is the howling sound of the wind over the ocean during a hurricane or Nor'easter. Also, a web site with earphones demonstrates the information that can be gleaned from the interaction of raindrops on the air-water interface

Air-Sea Interactions Working Group

- John Bane, University of North Carolina
- Tetsu Hara, University of Rhode Island
- Eric Lindstrom, NASA
- Roger Lucas, University of Hawaii
- Wade McGillis, Lamont-Doherty Earth Observatory
- John Morrison, North Carolina State University
- Jeff Nystuen, University of Washington
- Walt Oechel, San Diego State University
- David Smith, United States Naval Academy
- Jack Thigpen, North Carolina State University
- Sid Thurston, NOAA—OGP
- Christopher Zappa, Lamont-Doherty Earth Observatory
- Rod Zika, RSMAS, University of Miami

I. Ocean Macroecology

Cisco Werner (Moderator), David Mann (Rapporteur)

Marine ecosystems are experiencing dramatic changes globally. These changes reflect natural variability (Chavez et al., 2003; McGowan et al., 1998; Smith and Baco, 2003; Bograd et al., 2003; Hunt Jr. et al., 2002; Moline et al., 2004) and the influence of human activity on the oceans (Pauly et al., 1998; Jackson et al., 2001; Coleman et al., 2004). It is well documented that alterations in food webs have profound impacts on ecosystem structure and function (Hairston et al., 1960; Rosenzweig, 1973; Oksanen et al., 1981; Estes et al., 1998; Springer et al., 2003). Unfortunately, our ability to differentiate natural trends in food webs from human-induced changes is rarely possible. Although technological advances have permitted great advances in the non-invasive study of microbial food webs, our understanding of the secondary and higher trophic levels is very limited because the data were collected using traditional sampling capabilities. This is especially true for megafauna, which are actively mobile, have complex life cycles and sophisticated behavior, and whose population dynamics integrate the metabolism of the entire food web. Additionally, habitat utilization varies with the different components of the life cycle (Le Boeuf et al., 2000; Boustany et al., 2002) further limiting our understanding of this relationship in the oceans. And, specific to certain benthic communities, the remoteness and depth of abyssal plains renders extremely difficult research on many of the questions about the benthos and the biological and physical processes of their environment.

To open up a new era of study of the ecology in the oceans, the research community needs to develop a holistic view of ocean food webs with a focus on understanding the distribution and dynamics among all trophic levels.

Scientific Priorities

1. Define the physical and biogeochemical processes that population dynamics (feeding, behavior, spawning, and recruitment) for macro-organisms.
2. Quantify the top-down versus bottom-up processes in controlling fluctuations in top predator populations (e.g., fish, squid, mammals, and birds).
3. Understand the spatial and temporal variation of the bio-physical characteristics (e.g., hydrography, nutrients) that define megafauna habitat preferences.
4. Quantify how populations are connected through spawning and recruitment, which in addition to being a fundamental ecological question, will enable better management and forecasting of the population dynamics of economically important species.
5. Document long-term (long-period and episodic) fluctuations in ocean climate (ENSO, decadal oscillations, extreme events) that contribute to recruitment variability.

ORION will provide the capacity to deliver very high spatial and temporal resolution of macro-faunal populations over sustained periods while also providing the oceanographic context. These data are essential for understanding population processes of macro-invertebrates, fishes, sharks, sea birds, sea turtles, and marine mammals. Implementing technologies to track large numbers of individuals and relate habitat utilization to the environment from larval to adult life stages will provide an organismal view of the oceans (Block et al., 2002). Tracking pelagic fauna can be performed with a range of technologies from physical tags to chemical tags to passive acoustic tracking that would be monitored by ORION's coastal, regional, and global components. One long-term goal is to understand the environmental regulation of megafauna population dynamics.

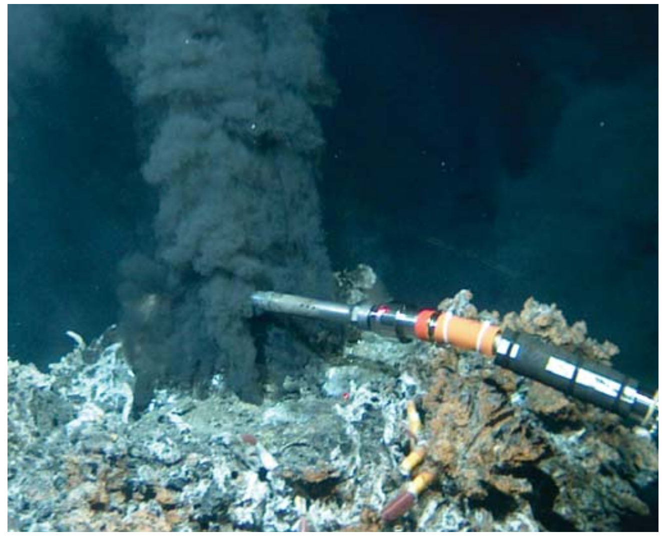


Figure I-1. Black smoker chemistry measured *in situ* at a hydrothermal vent on the East Pacific Rise. *Alvinellid* worms inhabit the area closest to the high-temperature vent, with *Riftia* tubeworms at the perimeter. *Alvin* Dive 3752, 16 Jan 2002, Chief Scientist K. Von Damm. Photo courtesy T. Shank, WHOI.

Example ORION Experiments

How do physical events, hydrography, and biogeochemical fluxes drive population dynamics of hydrothermal vent fauna over a mid-ocean ridge or ridge system?

Understanding vent community dynamics requires an integrated understanding of processes, including reproduction and recruitment, which are dependent on physical, biological, and geochemical factors varying in space and time. For example, faunal distribution is modulated by magmatic and tectonic events that alter the sub-seafloor plumbing, fluid flux, and chemistry that support these communities (Figure I-1). These communities can be catastrophically impacted by volcanic eruptions and lava extrusions. Therefore, efforts to identify and quantify emergent temporal and spatial patterns in community dynamics needs to be of sufficient duration to assess both episodic and secular trends within ridge ecosystems. Although a five-year time line may be sufficient to study spawning, recruitment, and succession in these ephemeral vent systems, "capturing" an episodic event due to a tectonic change in plumbing or a catastrophic event such as a seafloor eruption will require sustained observations over 10 or perhaps 20 years (the time scale might depend on the particular ridge being studied, as the temporal dynamics differ on fast versus slow-spreading ridges).

The ORION program will enable a fundamental leap in our understanding of macrofaunal community dynamics at mid-ocean ridges. Data over an ecologically relevant scale can be collected using a comprehensive observing network consisting of mobile and fixed platforms. Temporal changes in macrofaunal community structure can be quantified using arrays of time-series digital still cameras and/or high-resolution video coincident with collocated measurements of chemical nutrients and temperature, as well as autonomous macrofaunal and microbial sampling devices. These time-series arrays can be complemented with repeated spatial surveys carried out by autonomous underwater vehicles equipped with cameras and biological and chemical sensors essential to the characterization of species and environmental variables. New-generation biological sensors might sample the molecular diversity of planktonic larval stages using technologies similar to the Environmental Sample Processor (ESP) developed by MBARI (Scholin et al., 1998). These measurements would be complemented with data from moored time-series plankton pumps and/or sediment traps. For these experiments, it is critical that the observatory provide sustained physical (e.g., seismic and physical oceanography) and biogeochemical (e.g., microbial abundance in water column and vent-fluid chemistry) measurements. To observe vent communities comprehensively, an observatory that has high data bandwidth (needed especially for video), significant power (e.g., to enable *in situ* sampling via hydraulic manipulators), and real-time intervention capabilities (e.g., changing sampling rate in response to a video observation) is required.

In addition to seafloor and near-bottom observations, detailed three-dimensional measurements need to be recorded throughout the water column to understand the coupling of macrofaunal community dynamics to pelagic processes. For instance, water-column chemistry may provide settlement cues for planktonic vent larvae. Three-dimensional characterization of vent plumes and hydrography above the ridge axes are critical to answering questions such as: Do vent plumes enhance larval dispersal of benthic organisms through buoyancy, stratification, and shear in the water column? Are vent larvae in the water column attracted to hydrothermal vent plumes?

The ORION experiment described above can be connected to processes identified by the Fluid-Rock Interactions Working Group and the Benthic-Pelagic Coupling Working Group, as well as to the third experiment, described below, from the Macroecology Working Group. Specifically, our study of macrofaunal community dynamics would connect to the time-series studies of microbial dynamics discussed by the Fluid-Rock Working Group. An interesting link with the Benthic-Pelagic Coupling Working Group includes: Do vent plumes transport nutrients and/or primary producers from the benthos to the upper water column? If yes, is this an important contribution to upper water column primary production? Questions linked to the third experiment described below by the Macroecology Working Group include: Do pelagic megafauna respond to vent plumes? Do marine mammals respond to transient acoustic events at the mid-ocean ridge (i.e., seismic activity)? An observatory would enable tracking pelagic megafauna, 3-D characterization of vent plumes, as well as recording the seismic activity.

What are the limits of predictability for fish spawning and recruitment?

Many marine fishes have a bipartite life cycle, with a dispersive planktonic larval stage. Some, such as groupers and snappers, have a relatively sedentary juvenile and adult stage, while others, like salmon and tuna, have a highly pelagic adult stage. Thus, to predict the distribution of newly settled recruits, it is necessary to understand how physical oceanography interacts with the animals' biology. This predictive ability will allow fisheries managers to better manage fisheries and can be used to determine the location and efficacy of Marine Protected Areas (MPAs) (Polovina et al., 2000; Polovina et al., 2003).

ORION will provide needed data on the life history of fishes. Specifically, ORION will provide context in terms of oceanographic data, models of circulation, and data on phytoplankton and zooplankton community structure that could be driving fish population processes. ORION will enable scientists to tag fishes, invertebrates, and marine mammals and follow their movements. This type of work has not generally been possible in the past because of financial and infrastructure considerations. Advances in the study of population connectivity have been hindered by the physical model output not being delivered in a form that can be integrated with biological data. It is important to develop physical models that can be directly linked to biological data collected by ORION (Cowen et al., 2004).

More-focused questions to tackle (specific to the southeastern region of the United States) are: How does physical forcing drive spawning and recruitment of groupers and snappers in the Gulf of Mexico, Caribbean, and South Atlantic Bight? How are separate populations connected and how does this relate to oceanographic processes? To answer these questions requires shelf-scale data collected from the Gulf of Mexico, Caribbean, and South Atlantic Bight. Endurance lines in the South Atlantic Bight and the Gulf of Mexico have already been proposed. To complement these lines, we find it critical that a coral reef ecosystem be included in the ocean observatory network and therefore propose the addition of an Endurance line cross shelf (from southern Florida to the Bahamas; see Figure I-2). No other coral reef ecosystem line is included in the proposed sites. Pioneer arrays and moorings will also be needed at spawning sites and over ranges that could be covered by larvae based on the physical models of currents and larval lifetimes.

Within one to two years, spawning sites of groupers and snappers can be identified with a combination of technologies including passive acoustics of fish courtship sounds (Figure I-3), AUV-based surveys of grouper and snapper egg abundance, and plankton recorder data from moorings. Pioneer arrays would be essential to this effort. Models of egg and larval transport could also be developed along with models of the physical oceanography to create probability distribution maps, and to create the backbone upon which a forecasting system can be built.

Figure I-2. A proposed Endurance line study site (outlined by the yellow box). The array could be anchored with either cables or moorings. The proposed location would focus on studying coral reef ecosystems and the importance of the Florida Straits as an important connection between the Gulf of Mexico/Caribbean and South Atlantic Bight. The photo of Florida was provided by the space shuttle.

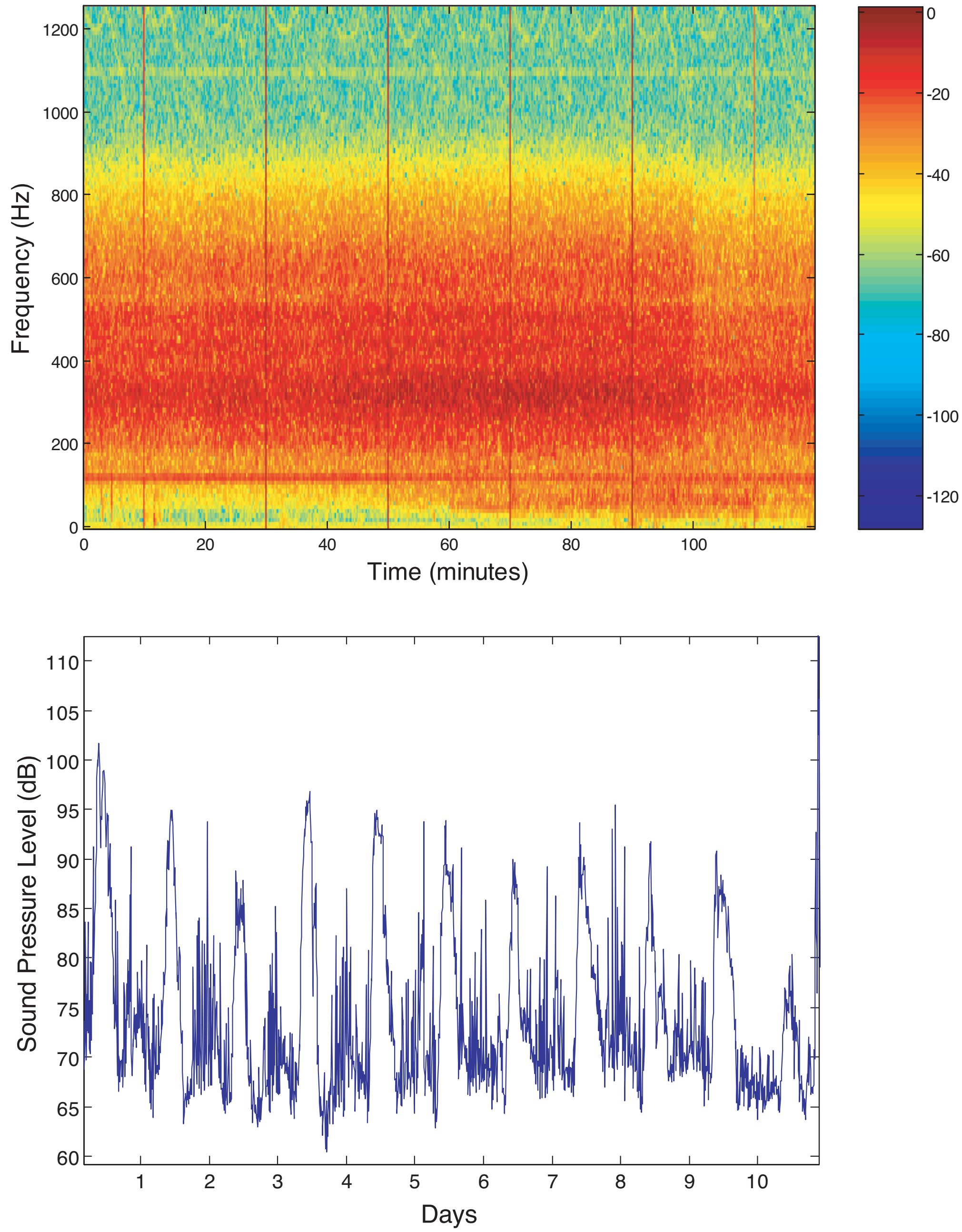


Figure I-3. Top: Sound production by croakers at the LEO-15 ocean observatory showing sustained sound production at night associated with spawning over a two-hour period. Bottom: Passive acoustics provides continuous time series data on reproductive activities of soniferous fishes on the same temporal and spatial scales as oceanographic measurements. Figure courtesy of David Mann, University of South Florida.

By studying the same populations over five years, we can determine the stability of spawning locations and variability in timing of spawning, and how this relates to oceanographic features. Data on larval behavior (e.g., directed swimming and diel vertical migration) can be collected with AUVs and multiple plankton recorders. The larval behavior can then be included in the physical models for predicting recruitment patterns. We will begin to understand how populations of fish and other ecologically and commercially important species vary over large spatial scales through larval dispersal, and how this contribution varies interannually. This information can be used in the design of MPAs and assist in ecosystem-based decisions.

A twenty-year time scale will be important for understanding the impact of long-term climatic events on the timing and place of spawning and variability in recruitment, and how this impacts adult population structure. By this time we expect to have made significant strides toward establishment of forecasting systems of the spawning, recruitment, and ultimate stock size of commercially important species.

How does physical and biological forcing drive the feeding, behavior, and migration of pelagic fishes, sea turtles, seabirds, and marine mammals?

Marine mammals and other long-lived top predators integrate resources over a large range of spatial and temporal scales (Costa, 1991; Ainley et al., 1995; Le Boeuf et al., 2000; Block et al., 2002; Hunt Jr., et al. 2002). They display short-term feeding behaviors that respond to prey aggregation, and longer-term behaviors that include feeding at multiple patches (Guinet et al., 2001). Feeding areas may be separated from breeding areas by tens to thousands of kilometers (Le Boeuf et al., 2000). Links among feeding, behavior, and migration, which work at multiple temporal and spatial scales, are not well understood. For example, blue whales will cease feeding on prey aggregations in the Southern California Bight to move to prey aggregations in Monterey Bay over a period of a few days (Croll et al., 1998). We have no information on the factors that make movements between prey patches separated by hundreds of kilometers an effective foraging strategy (Figure I-4).

Specific questions include: What oceanographic factors are responsible for the long-term changes in marine mammal populations (5 to 20 years), and how sensitive are different life history patterns to short- versus long-term oceanographic signals (e.g., ENSO and PDO) (Fraser et al., 1992; Smith et al., 1999; Hunt, Jr. et al., 2002). We know that there are considerable year-to-year variations in recruitment (cohort strength) that appear to be associated with changes in food availability driven by physical and biological oceanographic phenomena (Ainley et al., 1995; Hunt, Jr. et al., 2002). Island breeding species like pinnipeds and seabirds are particularly appropriate for comparisons between rookeries that occur across oceanographic regions (separated over large distances). For example, the California Current System (CCS) is modulated over several time scales (e.g., upwelling, fronts, ENSO, PDO) (Bograd and Lynn, 2003). Pioneer arrays and Endurance lines located at key sites (Monterey Bay, Point Conception, and southern California Bight) coupled with appropriate models will provide the necessary information on oceanographic habitat. The behavior of the animals will be monitored using electronic satellite tags or passive acoustics as they move through the region (Croll et al., 1998). Environmental data collected with tags on the animals will provide very-fine-scale information on the physical environment (Boehlert et al., 2001; Charrassin et al., 2002; Lydersen et al., 2002). The goal is to collect data allowing the spatial and temporal lag between predator-prey responses and primary production to be measured. There is both a spatial and temporal lag as energy moves up the food chain from the sites of primary production (Fiedler et al., 1998). We will also be able to answer which physical forcing processes are responsible for creating and maintaining prey patchiness, and which of these support efficient predation (Spear et al., 2001; Fielder et

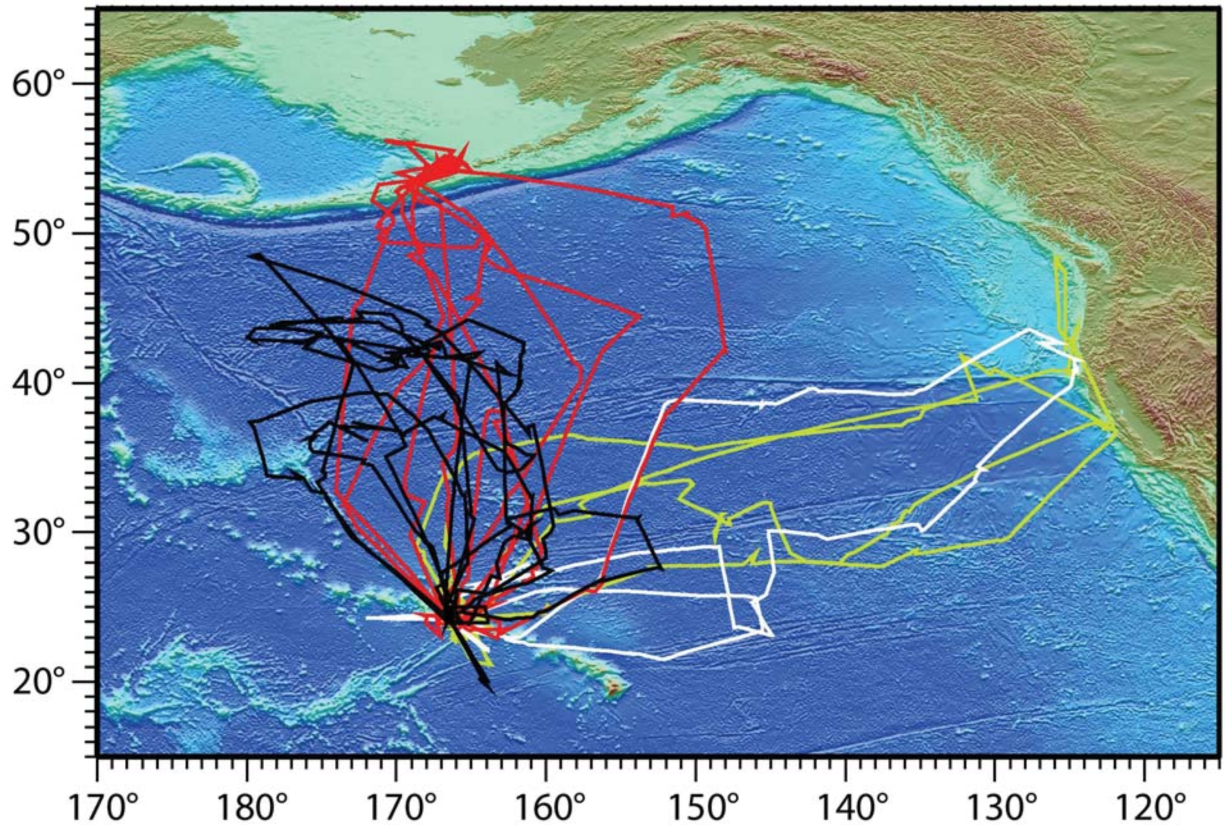


Figure I-4. Tracks of two Laysan albatross (black and red) and two black-footed albatross (white and yellow) over single foraging trips from the leeward Hawaiian Islands. Like many top predators, a foraging trip integrates resources over many scales. These birds traveled over much of the North Pacific to feed within mesoscale features that are considerable distance from their island rookery. Figure courtesy of Y. Tremblay, S. Shaffer, and D. Costa, unpublished).

al., 1998). Further, we need to know whether predators can detect these features to locate prey. These data would allow several ecology-related questions to be addressed (Table I-1).

To tackle these science issues requires a range of technologies, including hydrophones (single and vertical arrays along Endurance lines for real-time localization). The required hydrophone bandwidths are 0 to 2 kHz for fish sounds for marine mammals, 0 to 150 kHz and acoustic tags operating at 30 to 100 kHz. A range of chemical and environmental sensors will measure S, O_2, N, P, Fe, Si, Cl, turbidity, chlorophyll-*a*, and biochemical oxygen demand (BOD). Chemical sensors for measuring reduced compounds such as hydrogen sulfide or methane may be needed for benthic studies at seeps and vents. Physical sensors will measure salinity, temperature, and currents. Active echosounders (multibeam and imaging [e.g., dual-frequency identification sonar, or DIDSON]) will be needed. Finally, a range of imaging technologies will need to be used (high-resolution still cameras, high-definition video, lights, low light cameras, bioluminescent detection, crittercam). All sensors should be able to be deployed on all platforms (fixed-cabled, moorings, AUVs, gliders).

Table I-1. Marine mammal ecology questions to be addressed by ORION.
Does marine mammal foraging affect the structure of marine community structure or the behavior of their prey (top-down control)?
Has the reduction in great whales due to whaling resulted in direct or indirect effects in oceanic communities (Springer et al. 2003)? We are now in a recovery of some marine mammal populations: does this have a top-down effect on the ecosystem?
Has reduced competition for prey (fewer whales) resulted in more krill available for other predators such as sea birds (Fraser et al., 1992)?
Has the availability of fewer whales as prey for killer whales caused prey switching and associated changes in the abundance of other prey (seals, sea lions, and sea otters) (Estes et al. 1998; Springer et al. 2003)?
Do fewer whales result in reduced nutrient transport to the benthos (Smith and Baco, 2003)?
Are prey aggregations affected by marine mammal predation? Or are these aggregations only due to physical forcing?

Data Policy, Management, and Archive Needs

ORION must ensure open access to data. There is, however, the need for a policy of restricted access for some amount of time for some data (1 to 2 years) (e.g., high-quality benthic images). Access to quality-controlled core data in as near real-time as possible (e.g., salinity, temperature, currents) is needed. Data obtained for the community should be immediately available, with a one-year delay before full public access. Macroecology has unique issues regarding data. For example, tagged tuna with a live web broadcast of location could be used by fisherman to locate and catch fish in real time. Note also that there are concerns about inappropriate use of data by advocacy groups. It is important that these concerns be addressed when developing a data policy.

Ocean Ecology Working Group

- Roy Armstrong, University of Puerto Rico
- Stace Beaulieu, Woods Hole Oceanographic Institution
- Daniel Costa, University of California, Santa Cruz
- Duane Edgington, Monterey Bay Aquarium Research Institute
- John Hildebrand, Scripps Institution of Oceanography
- David Mann, University of South Florida
- George Matsumoto, Monterey Bay Aquarium Research Institute
- Jim Miller, University of Rhode Island
- Francisco Lopez Pagan, University of Puerto Rico
- Nancy Penrose, Neptune, University of Washington
- Sarah Ross, NOAA
- Hanumant Singh, Woods Hole Oceanographic Institution
- Cisco Werner, University of North Carolina, Chapel Hill

J. Plate Dynamics

Mark Zumberge (Moderator), Del Bohnenstiehl (Rapporteur), Jeff McGuire (Contributor)

It has been 40 years since the plate tectonics revolution. With that revolution came an understanding of how movement and interaction of tectonic plates are responsible for the formation of ocean basins, uplift of mountains, rifting of continents, and generation of the island arc volcanoes and zones of earthquakes surrounding the Pacific Ocean (known as the "Ring of Fire"). This revolution has had a dramatic impact on society, providing increased knowledge of why and where earthquakes and volcanic eruptions will occur. There still remain many unanswered questions, particularly with regard to the forces acting on plates, how plate boundaries interact and deform, and the links and feedbacks that exist among tectonic, magmatic, hydrothermal, and biological processes. For example, is plate motion driven from pressure developed at spreading centers, traction along the base of the plate from moving asthenosphere, or traction from subducting slabs?

To address these issues requires an ability to study episodic events. Marine geophysicists have long recognized that by observing the styles and timing of deformation prior to, during, and after events (e.g., earthquakes, volcanic eruptions, diking) it should be possible to examine and determine cause and effect relationships among major processes. Increasing our knowledge of the nucleation and rupture processes of earthquakes, for example, requires that measurements be made in the immediate vicinity of the fault, such as along ridge crests, at subduction zones, and at oceanic transforms, and that measurements be made prior to, during, and after the event.

Scientific Priorities

1. Determine the processes that control episodic deformation and magmatic activity at mid-ocean ridge plate boundaries.
2. Determine the importance of and controls on intraplate deformation, stress fields, and earthquakes.
3. Improve estimates of the earthquake hazard associated with great earthquakes along subduction zones.
4. Determine the relationship between the geologic structure of fault zones and the earthquake ruptures on those faults.
5. Define the role of fluid migration (water, magma, gas) in the construction of oceanic crust at mid-ocean ridges and in back arc basins.

Progress, however, has been limited by the difficulty involved in "capturing" these events. Event detection requires continuous, long-term deployments of instrument arrays. Although many of the necessary instruments exist (e.g., hydrophones, conductivity sensors, pressure sensors, current meters, seismometers), deployments in the ocean have been limited by power and bandwidth to months instead of to years. Although existing land-based seismographic stations allow for long-term monitoring, they typically record only the largest earthquakes in remote ocean areas and do not provide the level of accuracy needed to examine the details of fault location and motion at oceanic plate boundaries. *The OOI will provide the power, bandwidth, and communication to deploy the needed suites of continuously recording instruments and sensors to capture events, and to monitor pre- and post-event activity, thus allowing us to examine the links among processes, to determine cause and effect, and to bring us to an understanding of the role such events play in plate motion.* The OOI offers the opportunity to examine tectonic and magmatic processes in distinct environments, to study the full spectrum of deformation at plate boundaries and within plates, and to better understand the rheology in the crust, lithosphere, and upper asthenosphere.

Example ORION Experiments

During the next decades, long-term geophysical observations that will be made possible using the OOI will allow us to capture and examine significant eruptive and deformation events in a range of environments. Data on conditions prior to, during, and after these events will allow us to understand the kinematics, deformation, and driving mechanisms for plate motion and related hydro-tectonic interactions. Below are some specific examples of what could be learned about processes occurring within and at plate boundaries.

1. How is seafloor spreading partitioned between magmatic and amagmatic extension, and what is the space-time variation in magmatic and tectonic activity associated with the creation of oceanic crust?

Much can be learned about cause and effect relationships and the coupling among tectonic, magmatic, hydrothermal, and related biological processes at mid-ocean ridges by carrying out long-term, detailed seismic and geodetic monitoring at sites that exhibit different histories of magmatic activity and tectonic extension. Two contrasting sites that are well suited to such study are located on the Juan de Fuca Ridge: one on the Endeavour Segment where the youngest lavas exposed on the seafloor are ~10,000 years old and where faults predominate, and one on the more magmatically robust Cleft Segment where very young lavas (<20 years) are exposed. Arrays of seismic and geodetic instruments with apertures of a few kilometers will be placed along each of these segments to obtain adequate resolution to document the links and feedbacks among seismic activity, crustal deformation, magma movement, and dike emplacement (Figure J-1). Local seismic networks consisting of a dozen seismometers will be spaced 2 to 3 km apart along 10-km-long sections of ridge at each of these hydrothermally active segments. A combination of short-period, three-component seismometers, and broadband seismometers will provide accurate locations and focal mechanisms for small micro-earthquakes and allow long-period tremor signals, often produced by fluid flow, to be recorded.

Corresponding arrays of acoustic geodetic sensors at Cleft and Endeavour segments will document the distribution of extension across the respective ridge segments. These arrays will be supplemented by tiltmeters, absolute pressure gauges, and absolute gravity meters to record surface deformation that results from larger earthquakes and/or magmatic inflation/deflation; electromagnetic instruments to measure fluid and magma movement in the sub-seafloor; and thermistors/thermocouples, current meters, optical sensors and cameras, acoustic imaging, and geochemical sensors emplaced within hydrothermal vents to record changes in hydrothermal systems. Power, communication, and bandwidth to these instruments will be provided via a series of cable nodes or "junction boxes." These data will be supplemented by data collected by an AUV, docked at the cable until an event occurs, that can carry out water column sampling and repeat microbathymetry and side-scan sonar surveys. The sum of all of these data will allow detailed examination of the contributions of dike intrusion and extensional faulting to spreading, and of the feedbacks that exist among faulting, magma movement, fluid flow, hydrothermal activity, and related biological communities along mid-ocean ridges.

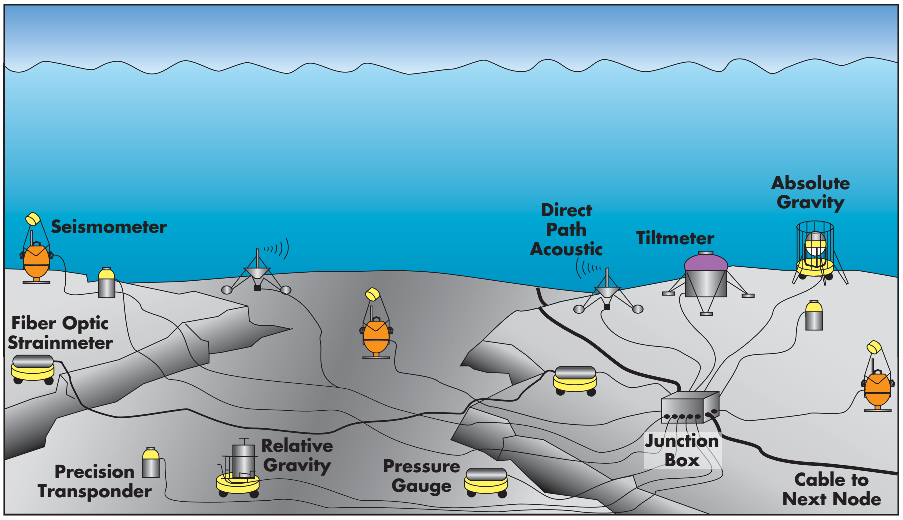


Figure J-1. Cartoon of a seafloor geophysical observatory that contains seismometers and a variety of geodetic instruments.

2. What is the rupture area for a megathrust earthquake and how does it vary along the subduction zone? What is the associated stress regime and its variation through the earthquake cycle? What processes (e.g., fluid pressure, sediment composition, alteration) control the updip aseismic to seismic transition within accretionary prisms?

There is still much to learn about the physical processes preceding and accompanying megathrust earthquakes. Figure J-2 shows a 2-D elastic model of deformation for a locked subduction zone, and the geographic location of the locked zone. Prior to a megathrust earthquake, when the fault zone is locked, the overriding plate is flexed upward. The seaward limit of the locked zone, a primary control on tsunami size, is not constrained by land geodetic data. The landward limit of the locked zone, critical for determining the dimensions of the rupture zone and predictions of earthquake shaking, is also located offshore. Long-term geophysical observations in the ocean, specifically seafloor geodetic data, are required to extend profiles based on data collected on land and offshore, and accurately model this deformation and constrain the seaward and landward limits of the locked zone. Fault rupture potential is also affected by pore fluid pressures. Sensors placed on the seafloor and in boreholes can be used to measure fluid flow and pore fluid pressures. Fluid pressure may control both megathrust and smaller earthquake rupture.

To examine the effects of frequent earthquake shaking on fluid processes within the accretionary prism, including prism deformation and fluid processes that affect biological communities, a subduction and seafloor wedge observatory will be placed over the Nootka Fault zone. The Nootka Fault zone, extending southwest from Victoria Island, will be accessible from the cable planned for NEPTUNE Canada, and could conceivably produce significant earthquakes within five years. A 50-km transect of ~10 broadband seismometers and strong-motion accelerometers will be deployed across the fault. Geodetic sensors will measure tilt and vertical uplift; borehole temperature and pressure sensors will track conditions within the sediment; fluid monitoring and sampling from boreholes will provide further information about fluids within the prism and how fluid flow and composition are affected by intermittent shaking.

3. How do spatial variations in geology, thermal structure, and fluid pressures control whether a fault ruptures during infrequent large earthquakes or undergoes relatively steady, aseismic creep?

Oceanic transform faults exhibit simpler geologic, thermal, and tectonic conditions than continental faults. On a global scale, oceanic transforms fail predominantly by aseismic slip, whereby the cumulative strain accommodated earthquakes

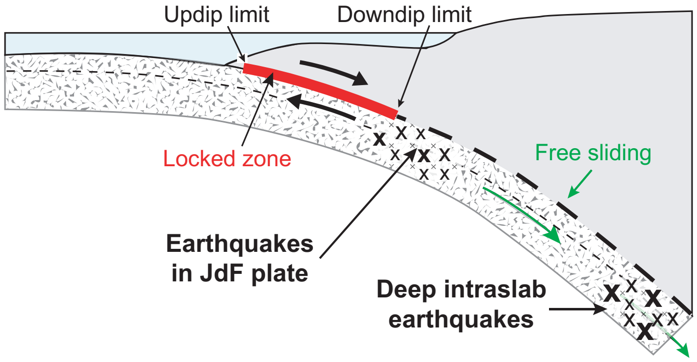
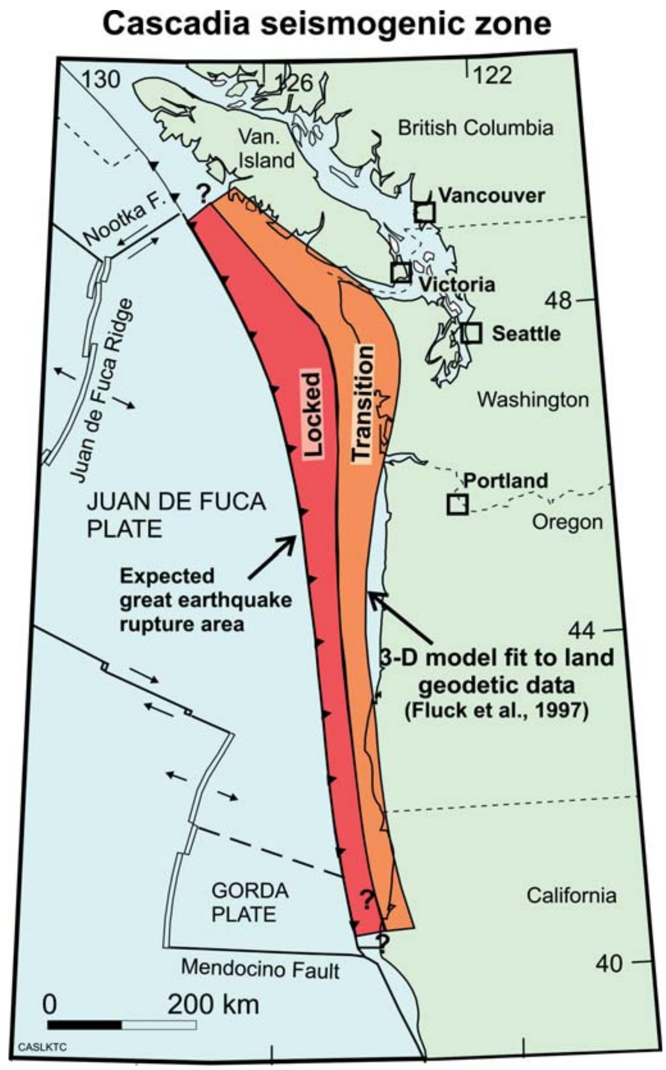


Figure J-2. Schematic diagram and plan view showing the locked and transition zones on the subduction thrust fault along the Cascadia margin of western North America. Locations of the locked and transition zones are estimated from dislocation modelling of the current deformation. (Plan view is modified from Fluck et al., 1997).



on a given transform fault is typically not sufficient to account for the long-term motion of the plates. This behavior is essentially opposite that of continental transforms, where slip is accommodated almost entirely during earthquake events and creeping aseismic segments are rarely observed. Oceanic transforms thus offer natural advantages for constraining the mechanical processes involved in faulting and lithospheric deformation. Additionally, a comparative wealth of experimental rock mechanics data exists for the limited number of rock types present in oceanic lithosphere. To understand the dynamics of oceanic transforms and their transition from seismic to aseismic behavior requires combining this rock mechanics knowledge with site survey information about the spatial distribution of various rock types and a data set of dense seismic and geodetic recordings of a large earthquake.

A portion of the Blanco Transform (at about 128°W, 43.5°N has ruptured in frequent large (magnitude 6.2 to 6.4) earthquakes in the recent past (1968, 1981, 1985, 1994, and 2000). These events are interesting not only for their high frequency in a relatively limited region, but also for the geologic setting in which they occur. In this region, termed the Blanco Ridge, the fault is expressed as a long, elevated ridge that is inferred to be composed of serpentine. Serpentine is one of the more unusual rock types known in terms of its frictional properties and is a potential explanation for the predominance of aseismic slip on oceanic faults, yet the large earthquakes happen where (or possibly beneath where) the serpentine is most abundant. A minimum of 15 stations within this roughly 20 by 50 km area will be emplaced, each consisting of a broadband seismometer and strong-motion accelerometer. These instruments will monitor activity prior to, during, and after the next large earthquake, allowing determination of the depth range of background seismicity, rupture area, propagation velocity, and region(s) of the fault that slips aseismically. For these data to be analyzed with state-of-the-art techniques, these instruments require the precise timing and power capabilities over time periods of years to decades that the OOI can provide. Moreover, the expected 30-year

(??) lifetime of OOI will probably span multiple large (M>6) earthquakes in this region. The seismic stations will be supplemented with acoustic-GPS sites located on either side of the fault, and direct-path ranging systems spanning the fault at two locations within the seismic array. The resultant observations of fault behavior will be compared to predictions of rheology based on rock mechanics, observations of spatial variations of rock type, and models of thermal structure. Note that the acoustic-GPS system can also serve as a local AUV acoustic navigation and communications network.

4. How and why do stresses vary with time across a plate (as indicated by small earthquakes and *in situ* stress measurements)?

The plate-scale geophysical observatory (e.g., Juan de Fuca Ridge) will be used to investigate plate boundary interactions. It is now clear from recent studies on land that stress transfer is a fundamental mechanism controlling fault interaction and aftershock clustering. There are also hints from recent studies that oceanic plates can transmit stresses rapidly over hundreds of kilometers. For example, the 400-km-long band of intense mid-plate seismicity observed in the Gorda Plate in 1991 to 1992, and shown in Figure J-3a, ceased in this area following a magnitude 7.2 earthquake in the Cape Mendocino region. As shown in Figure J-3b, seismicity levels on the Gorda Plate decreased dramatically in the years after this event. It has been proposed that the Cape Mendocino event relieved stress in the Gorda Plate by triggering movement in the adjacent subduction zone. Data recorded by seismometers within the Gorda Plate, as part of the plate-scale observatory, are necessary for determining the orientations of the active faults, which can then be used as a necessary input for testing the stress triggering hypothesis in a quantitative way that is not possible with the currently available (primarily hydroacoustically derived) information.

Outreach

Projects to monitor and "capture" significant events, such as earthquakes and volcanic eruptions, will appeal to a wide audience, from young children to inquisitive adults, and provide unique opportunities to educate those who normally are not engaged by complex science issues, as well as to budding researchers.

Informal Education: A number of web-based programs that follow event-response efforts already exist, as do museum displays, and there is a history of media involvement following major and even minor earthquakes and volcanic eruptions. Efforts to involve the media in pre-event monitoring should be encouraged. Museum exhibits and web sites can be created that allow the general public to help monitor the various sites being supported using the OOI. At many of the planned sites, those engaged in the pre-event monitoring will be rewarded with the opportunity of watching the rapid changes that occur leading up to, during, and following the events. These outreach efforts will bring home to the general public the dynamic nature of the ocean floor, and will provide them with a greater understanding of the dynamics that shape the Earth on which we live. In addition to helping with the monitoring process, a number of hands-on involvement opportunities are envisioned, including contests for instrument and/or experiment design.

Formal Education: Within the ORION Office there should be a central person, or sub-office, that PIs can access:

- to obtain well-designed templates (geared to teachers, students, and the public) for use with projects that will make the process of displaying data straightforward (e.g., an easy to use "plug and play" template)
- to find teachers interested in going to sea, or interested in pairing with PIs to produce educationally useful materials for web sites or other materials
- to facilitate pairing of educators/PIs at early stages of the project (i.e., at the proposal writing stage); developed partnerships would carry through the project
- for information about national education standards, and how these could be met with modules designed for instrument development, monitoring efforts, event response efforts, and data analysis efforts

At the undergraduate level, direct involvement of undergraduates through internships should be a priority.

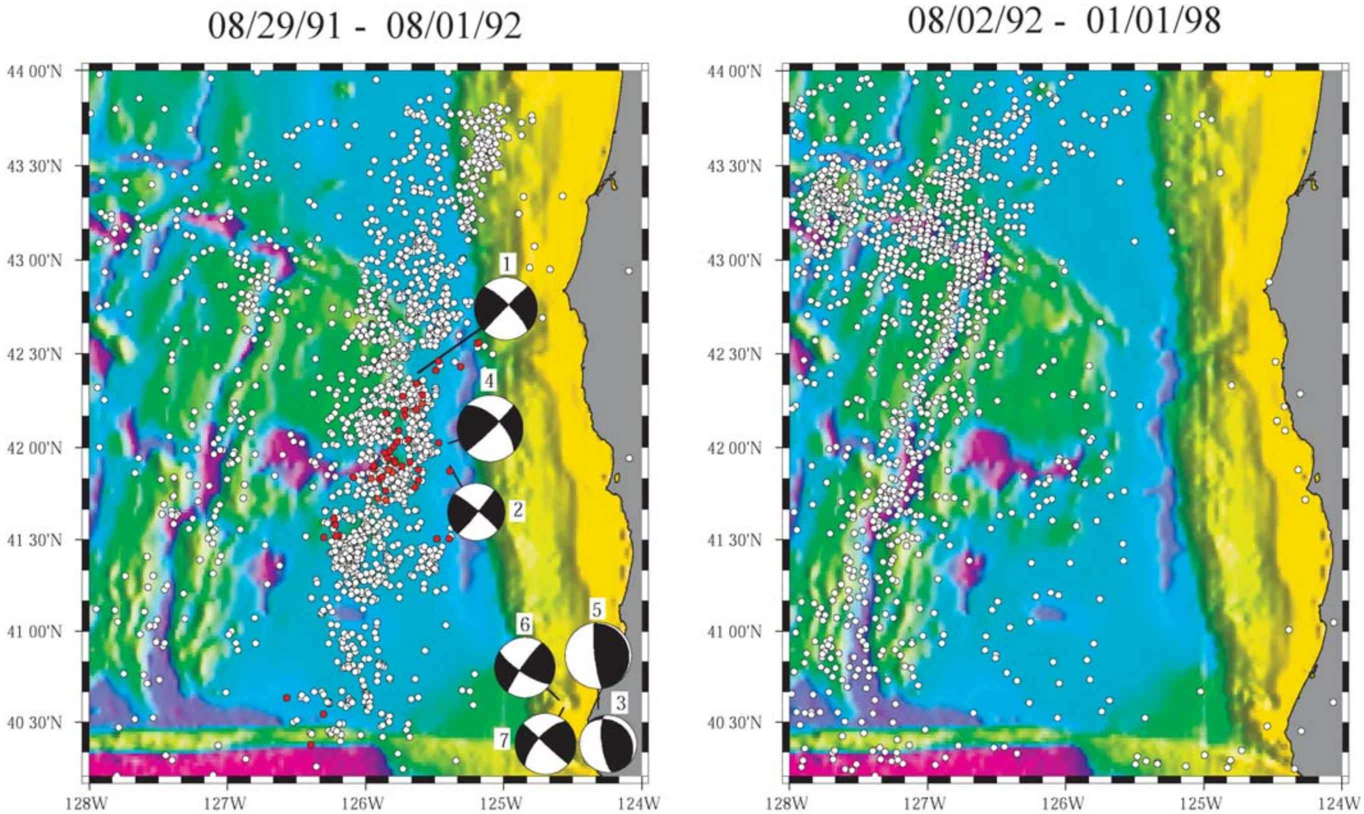


Figure J-3. Distribution of earthquake epicenters in the Gorda Plate region derived from both land-based networks (red dots and focal mechanisms) and hydrophone arrays (white dots). The diagram at the left shows events recorded from August 29, 1991 through August 1, 1992, while the diagram at the right shows events recorded from August 2, 1992 through January 1, 1998. A band of hydroacoustically recorded microearthquakes in the middle Gorda Plate can be clearly seen in the left diagram but has effectively disappeared after July 1992. The only significant seismic event to occur in the region while the microseismicity band was active was the April 1992 Cape Mendocino earthquake sequence (with a magnitude 7.2 earthquake in the Cape Mendocino region). As shown by the figure on the right, seismicity levels on the Gorda plate decreased dramatically in the years after this event. It has been proposed that the Cape Mendocino event relieved stress in the Gorda plate by triggering movement in the adjacent subduction zone. Figure from Fox and Dziak (1999).

Keys to Success

While Earth's plates are defined by similar characteristics and boundary types, there are important differences among them, including rates at which they spread apart, sizes of individual plates, and rates at which subduction occurs. Clearly there is an advantage to studying the plates in a variety of settings and over a variety of scales. Given limits on funding and logistics, progress will best be made through collaborations with other national and international programs. A range of important questions will be addressed using the regional cable system, with a goal of establishing baseline deformation rates and beginning to understand stress distribution from the spreading ridge to the subduction zone.

Links to other programs that have observatory components, including IODP, Margins, and RIDGE2000, can be made to most efficiently examine differences that exist within different environments. Likely collaborative efforts include using a buoy observatory at the East Pacific Rise at 9° 50' N, and establishing plans for rapid response to detected events (in collaboration with the RIDGE2000 program). Other sites that are high in priority for study of plate dynamics include the slow-spreading Mid-Atlantic Ridge, the western Pacific (near the Mariana Trench—in collaboration with the MARGINS program), the Middle America Trench, as well as coastal sites at Pt. Barrow, along the San Andreas Fault and Borderlands, and within the Gulf of California.

Collaboration With Other Groups

Studies of the asthenosphere and of upper-mantle processes associated with plate motion will benefit from close coordination with groups studying global scale processes. By discussing buoy emplacement with groups interested in deep Earth processes and with ocean circulation and climate, plans can be made for buoy observatories at locations that will provide data to address a wide range of important Earth structure, plate dynamics, ocean circulation, and climate-related questions.

Site Survey Requirements

It is important to recognize that, before deploying cabled observatories or buoyed observatories, the relevant sites will require surveying to plan the optimum deployment strategy and the best science return on the infrastructure investment. In this regard, we would do well to partner with allied programs (e.g., RIDGE2000, IODP, MARGINS) to share costs. For focused study areas, the site surveys would include bathymetry (near bottom and sea surface), 3-D seismic from the surface, ocean bottom seismic observations, side-scan sonar, seafloor geology, sampling of fluids (including CTD) and rocks, and documentation of biological communities. The intensity of site surveys will vary with the location. Near spreading centers, for example, more microbathymetry might be called for to form the comparison basis for subsequent repeat surveys that follow an eruption event. The expense of site surveys will add up to a significant portion of the budget for the entire ORION project and should not be overlooked.

It also will be important to carry out a quantitative analysis of the best array geometry for each array of instruments (e.g., the minimum spacing of seismometers and geodetic sensors at plate boundaries and plate interiors needed to resolve questions), considering both cost and science requirements.

Instrumentation Needs

While many instruments needed for seafloor geophysical observations already exist, efforts to "capture" events and their consequences will require development of some new instrumentation as well as modifications of existing instrumentation for deployment at nodes in a cabled observatory. Needs also exist for development of specialized equipment for specific experimental work targeted at individual sites or phenomena, and for rapid responses to events.

Plate Dynamics Working Group

- Jamie Austin, University of Texas at Austin
- Rodey Batiza, National Science Foundation
- Steve Bohlen, Joint Oceanographic Institutions
- Del Bohnenstiehl, Lamont-Doherty Earth Observatory
- Jim Brey, University of Wisconsin
- Kevin Brown, Scripps Institution of Oceanography
- Suzanne Carbotte, Lamont-Doherty Earth Observatory
- Dave Chadwell, Scripps Institution of Oceanography
- Vicki Clark, Virginia Institute Of Marine Science
- Robert Detrick, Woods Hole Oceanographic Institution
- LeRoy Dorman, Scripps Institution of Oceanography
- Patricia Fryer, University of Hawaii
- Don Hussong, Fugro Seafloor Surveys
- Jeff Karson, Duke University
- Gene Massion, Monterey Bay Aquarium Research Institute
- Margaret Olsen, Southeast COSEE
- Fred Spiess, Scripps Institution of Oceanography
- Maurice Tivey, Woods Hole Oceanographic Institution
- Maya Tolstoy, Lamont-Doherty Earth Observatory
- Doug Toomey, University of Oregon
- Spahr Webb, Lamont-Doherty Earth Observatory
- Mark Zumberge, Scripps Institution of Oceanography

K. From Rivers to Continental Slopes

Jack Barth (Moderator), Richard Dewey (Moderator), Janet Campbell (Rapporteur)
Collin Roesler (Moderator), Heidi Sosik (Rapporteur)
Daniel Rudnick (Moderator), Emmanuel Boss (Rapporteur)

Although the continental margin represents only about 8% of the surface area of the world's oceans, it represents a region that is disproportionately important to humans and global biogeochemistry. For example, despite its small area, the coastal ocean represents up to 30% of the total global ocean productivity and more then 90% of the world's fish catch. The coastal ocean represents the major filter between the terrestrial and open oceans with the majority of the terrestrial inputs being trapped and remineralized on the continental margins. Evidence is mounting that human activity is altering nutrient patterns and food web structure and these changes are likely to increase in the coming decades with the projected development along the world's coastlines.

Many biological, chemical, and physical processes on continental shelves operate over relatively short temporal and spatial scales. Episodic phenomena such as storms have particularly large impacts on food webs, material transport, and the biogeochemical cycling of elements in shallower waters. Recurring phenomena such as ENSO and Gulf Stream meanders also strongly affect shelf ecosystems over short temporal and spatial scales on the shelf. Adding to the oceanographic complexity of the shelf environment is the spatial variability of circulation patterns, which is significantly influenced by irregular shelf topography; our ability to interpret time-series data is limited by both insufficient observations and theory. Finally, the physical, chemical, and biological gradients at the interface between the continental shelves and the atmosphere, seafloor, land, rivers, and deep ocean basins are poorly understood and constrained. Knowledge of these gradients (both horizontal and vertical) is critical for estimating the advective fluxes that dominate local change, which in turn is important for understanding the biogeochemistry of shelf waters. Enhanced biological and chemical cycling rates at these interfaces are often orders-of-magnitude larger than those deeper in the water column and thus significantly influence the mean biogeochemical signature of the continental shelf ecosystems. Large-scale estimates and models do not always take into account system heterogeneity.

Scientific Priorities

1. Quantify the fluxes of energy and materials across continental margins.
2. Determine the relative importance of episodic versus periodic forcing on continental shelf ecosystems.
3. Quantify the influence of large-scale interannual and interdecadal ocean-atmosphere variability (e.g., ENSO, PDO, NAO) on continental margin ecosystems.

High-frequency, continuous, time-series measurements in broad-scale spatial arrays are required to resolve interdependencies among physical, biological, chemical, and geological variables. Because of the range of short- and long-term processes, quantifying mass fluxes of materials along continental shelves requires measurements more than once per hour over mesoscale spatial scales in order to sample the advection, transformation, and dispersal of particulate and dissolved material. Such data would enable modeling of system response to natural events and experimental manipulations. Long-term synoptic sampling should allow for the removal of many time-series aliasing difficulties. ORION offers the potential to collect the spatial time-series data required to address questions central to coastal oceanography.

ORION will provide fixed observational assets on continental shelves and in the overlying atmosphere to quantify spatial (horizontal and vertical) gradients in biogeochemical constituents at appropriate scales. To resolve the wide range of temporal and spatial scales at which biological, chemical, and physical processes act, ORION will also provide a distributed, integrated observing network composed of a variety of fixed and mobile platforms. Evolving technology is poised for deployment on these platforms and is just waiting for the *in situ* infrastructure to be in place. Given this, ORION will show tangible results within five years of the start of the coastal ocean experiments.

Example ORION Experiments

Three major research themes proposed by three working groups spanned time frames from daily to months (fluxes on shelves), to years (ENSO and NAO dynamics), to decades (climate changes occurring on shelves). Specific boundaries to be studied by ORION are listed in Table K-1 along with some of the major questions that need to be addressed by the continental shelf research community. The specific layouts of the ORION continental shelf observatories will likely be a function of the experiment conducted. Instrument spacing will vary depending on the gradients being measured and the specific deployment location on the shelf. Observation System Simulation Experiments (OSSEs) could be used to determine the placement of fixed and moveable assets for optimal results.

What are the fluxes of energy and materials across continental margins and how do these fluxes vary in space and time?

Quantifying mixing and elemental exchanges at system boundaries presents many scientific challenges. To sample at appropriate spatial and temporal scales requires a nested observing strategy, with instrument deployments providing higher spatial resolution in the inner shelf (~10 km) and at the shelf break, and higher vertical resolution in surface and bottom boundary layers within the ocean, and in the atmospheric MBL above the surface. The principal goal is to resolve exchange across interfaces on the shoreward side of shelf and at the shelf break, the latter involving enhanced vertical mixing near-bottom over the upper slope and horizontal exchange as well as along-isopycnal transport across the shelf break into the deep ocean.

Horizontal Array Design: Fine-spatial resolution (1 to 5 km) near features such as estuary mouths and capes. Cross-shelf spacing of fixed assets (moorings telemetering to shore) on a central transect across the feature should be 1 to 5 km. Similar spacing in the alongshore direction should extend about +/- 20 km. Fine cross-shelf spacing around the shelf break (a few to 5 km) is recommended. Coarser alongshore spacing to far field (~10 km over entire ~100 km region) is needed. These arrays should be complemented with mobile assets (e.g., gliders) in the far field (i.e., to set offshore and alongshore boundary conditions). Mobile assets should be used to better define short spatial scales (100 m to a few kilometers) within the study region and to track features and their edges. HF land-based radar should be used to get hourly maps of high-spatial-resolution surface currents (2 to 3 km in inner nest; 8 to 10 km to far field).

Vertical Array Design: Vertical array design should be optimized to investigate benthic-pelagic coupling, mid-shelf benthic-estuary/nearshore coupling, and air-sea interaction. The resolution should be: 1 m over the entire water column for temperature, salinity, chlorophyll fluorescence, and bio-optical properties; 2 m over the entire water column (<100 m deep) for velocity; 20 to 50 cm for velocity in surface and bottom boundary layers. A Vertical Profiling System (VPS) capable of 25 to 50 cm/s velocity can cover 200 m in 400 to

Table K-1. Boundary-Related Questions Requiring ORION Infrastructure	
Continental Shelf-Slope Boundary	How and where does boundary mixing influence maintenance of the oceanic thermocline structure, vertical mixing of nutrients, and horizontal transport of these properties into the interior?
	Is the boundary a source of non-local mixing in the interior?
	Is the boundary a source of micro and macronutrients, and carbon to the global ocean?
	What frequencies must be captured to understand processes controlling meridional overturning?
	What are the primary modes of variability of continental slope current systems and how is this variability modulated by large-scale climate signals in the atmosphere-ocean system?
Bottom Boundary Layer/ Benthic-Pelagic Coupling	What is the primary production contributed by benthic communities?
	What is the spatial variability in benthic physical and biogeochemical processes, substrates and organisms?
	What is the coupling of benthic and water column processes (e.g., vertical mixing and vertical transport in and out of the bottom boundary layer)?
	How significant is the net vertical transport along isopycnals intersecting the bottom?
Boundaries on the Mid to Inner Shelf (~80 m and shallower)	To what extent do river flows, coastal currents, nutrient fluxes, and biology change in relation to climate patterns and/or human influences?
	What are atmospheric inputs and what role do these materials play in biogeochemical cycles and productivity?
	What affects the timing and duration of seasonal cycles of productivity and biogeochemical cycles on the mid to inner shelf?
	What causes harmful algal blooms that are mostly found on the mid to inner shelf ?
	What processes control interannual fluctuations in larval recruitment and fish stocks?
	Does the inner shelf experience regime shifts?
	What is balance between Ekman-driven versus curl-driven upwelling?
Atmosphere-Ocean Boundary	What is the relationship between the surface and subsurface, especially immediately adjacent to the coast?
	What are the feedbacks between the coastal ocean and the overlying atmospheric boundary layer, for example, coastal upwelling and formation of fog?

800 s (6.6 to 13.3 minutes) and thus repeat the cycle every .5 to 1 hour. The VPS should be minimally capable of operating in 2 knot (1 m/s) currents and year-round wave conditions (up to 30 feet for PNW). Atmospheric sensors should resolve the MBL (order 200 to 500 m thick), especially near the coastal barrier (i.e., within about 10 to 20 km of the coast).

Atmospheric parameters to be measured include temperature, humidity, wind speed and direction, chemical concentrations (e.g., CO_2, DMS), and aerosols. (Note: AERONET is a worldwide network of aerosol monitoring sensors used to monitor air quality and provide input for interpreting satellite observations. Recently, a few such sensors have been located on platforms offshore, and this trend should continue). *Although ORION would not oversee the launch of a new satellite system, it cannot be overemphasized that access to satellite imagery is a key data requirement for the observatories. The ORION program could provide great leverage to NOAA and NASA to justify the launch of new satellite remote-sensing assets for the oceanographic community.*

The proposed arrays should be outfitted with a set of similar instruments that might include CTDs, ADCPs, optical sensors, fluorometers, oxygen and carbon sensors, and nutrient sensors (ideally measuring both macro and micronutrients). Biological measurements should include acoustics and video given high power and bandwidth capabilities of the proposed observatories. Core sensors would be complemented with exciting new techniques or sensors that are under development by individual PIs.

Because of the spatial heterogeneity on continental shelves, mobile platforms are needed in addition to fixed sensor arrays. The fixed observatory network for the shelf flux experiment should be complemented with floats (constant pressure, isopycnal, constant elevation above bottom, with behavior to mimic larvae), and smart tags and sensors. The bottom boundary layers need to be sampled with profilers (AUVs, gliders, "bouncers"), rovers capable of conducting measurements in sediments ("creepers," "diggers"), and platforms capable of maintaining constant elevation above bottom ("cruisers," "helicopters"). Inexpensive bottom pressure sensors should be developed and then deployed on ORION fixed platforms to measure bottom pressure gradients.

What is the effect of the El Niño-Southern Oscillation (ENSO) on coastal ecosystems?

The mechanisms by which the effects of ENSO arrive along the west coast the United States are poorly understood. One possibility is that ENSO is related to basin-scale to global-scale atmospheric anomalies that themselves affect coastal water properties. Along the West Coast there are two other mechanisms also at work: ocean wave propagation and advection. ENSO is known to cause coastally trapped waves, which propagate northward away from the equator. However, these waves seem not to be able to propagate past the Gulf of California, so their effect on the west coast of the United States remains questionable. Certain manifestations of ENSO (changes in water properties, arrival of different planktonic organisms) are likely to be caused by advection as ENSO modulates the boundary current systems (McGowan et al., 1998).

An observatory capable of resolving these processes requires a comprehensive network composed of a variety of platforms. Fixed stations, such as moorings with either profiling or fixed instruments will provide vertical and temporal resolution. Nearshore, where ecosystems may be affected by river plumes, fixed moorings should be roughly 100 m apart. In deeper waters (e.g., mid-shelf), moorings can be spaced about 1 km apart. Vertical resolution of a meter or less will be needed on all sensors to resolve the pycnocline, nutricline, and biological layers. Transitions in and out of ENSO or NAO cycles can begin abruptly, therefore the minimum sampling frequency should be daily. However, recording hourly forcing would be ideal because it would provide information about ENSO or NAO modulation of internal waves and other critical continental-shelf processes.

The ORION observational sensor networks should be capable of making profiling measurements. The most important physical measurements include temperature, 2-D velocity, pressure, sea-level height, and river discharge. Measurements of the subsurface light field and directional wave spectra are also high priority. Physical measurements should also include atmospheric fluxes of momentum, heat, and dissolved gases. Critical chemical measurements include the macronutrients (nitrate, phosphate, ammonia, silicate), oxygen, pH, CO_2, micronutrients (Fe, Zn, Mn), dissolved organic matter, and sulfur. Critical biological measurements include primary and secondary productivity rates, particulate organic carbon, chlorophyll, the general community composition of the fish, macro-zooplankton, phytoplankton, micro-zooplankton, and microbial community. Combined, these measurements will permit an in-depth assessment of the effects of ENSO on West Coast ecosystems.

A complete observational system will require much more than fixed platforms. Autonomous gliders and docking AUVs are needed to provide spatial extensions in both the

Table K-2. ENSO-Related Questions Requiring ORION Infrastructure
What are the changes in the community structure and function (abundance, activity, and distributions of taxa)?
How does ENSO affect timing, magnitude, and persistence of blooms?
How does ENSO affect biogeochemical fluxes?
How does ENSO modulate mesoscale ocean features (fronts, upwelling/downwelling, eddies)?
How does ENSO modulate storms (precipitation, wind, mixing, surface waves)?
How does ENSO modulate river/estuarine processes and inputs (fresh water, pollution, nutrients, turbidity)?
How are short temporal and spatial scales coastal processes modulated by ENSO-related atmospheric forcing and changes in ocean stratification?

horizontal and vertical. These three-dimensional subsurface maps of physical, chemical, and biological properties will complement satellite imagery that will resolve the physical and biological properties over the entire shelf. Satellite maps of water constituents will be combined with surface current maps, collected with HF radar, to determine the type of material being advected. Additional surface maps will be made with microwave radar (1.5 mile range with 5 m resolution) to define the spatial wave, current, and bottom topography.

The core observatory spatial and temporal measurements will provide a context for detailed process studies by individual research groups. Such focused process studies would likely include surveys conducted with ships, aircraft (strong encouragement to develop UAV was highlighted by this working group), ROVs, floats, and drifters. Note that another, similar experiment in the northeastern United States should focus on the North Atlantic Oscillation (NAO). This experiment would have a similar experimental layout as discussed above.

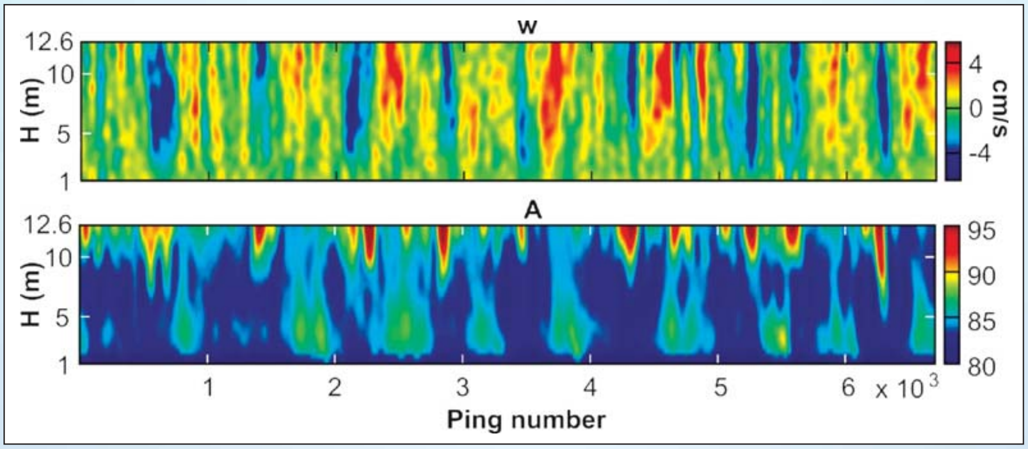
What is the relative importance of episodic versus lower frequency secular processes in regulating ecosystem structure on continental shelves?

Continental-shelf ecosystems reflect both local and external processes. Understanding the synergy between these processes is the key to understanding the structure and overall productivity of the shelf ecosystem and how it may change as a result of long-term secular changes. Characterizing the feedbacks between these processes is difficult because they span a wide range of spatial and temporal scales. For example, productivity on continental shelves along the northeastern United States is regulated by episodic storms, river plumes, shelf-slope exchange processes, and the climatological mean southerly flow from the north. The Northeast is experiencing secular changes as evidenced by significant decreases in salinity and increases in temperature in the Mid-Atlantic Bight (MAB) over the last decade (Mountain, 2003). Such secular changes raise a series of questions that can be addressed using ORION infrastructure.

To address secular changes occurring along the northeastern United States, a series of Endurance lines are proposed to provide cross-shelf decadal time series. These sampling rates would provide sufficient data to quantitatively understand the relative importance of episodic forcing and cyclical and secular processes on the MAB. A specific focus should be defining elemental budgets (carbon, nitrogen, phosphorus, and metals). These Endurance l would be augmented with shorter-duration Pioneer arrays that would collect data for process studies to aid in the interpretation of the time series. The Endurance lines should span the shore to the continental slope. The horizontal spacing of sensors should be on the order of tens of kilometers, however, vertical resolution needs to on the order of centimeters. This vertical resolution is required given the presence of numerous layers that are spatially extensive. For example, the thermocline on the MAB is very tight and has the strongest temperature gradients, with temperatures ranging from 25° to 8° C in only 50 m of water. This strong stratification is a key feature that dramatically impacts elemental cycling and the potential exchange with the atmosphere. Additionally, the thermocline and halocline are spatially distinct. The placement of the Endurance lines should be such to provide estimates of flow and material: (1)

Box 10. Cabled Observatory Discovers Supercharged Langmuir Cells

Contributed by Ann Gargett, Old Dominion University



Vertical velocity (w) and relative backscatter amplitude (A) associated with Langmuir "supercells"—Langmuir circulations that have deepened to the full depth of the water column at the LEO-15 observatory. H is height above bottom, and filtered vertical beam data is available below the minimum surface height over the record length, a period of ~ 2 h. The ample power and broad bandwidth provided by the LEO-15 cable allowed the continuous high frequency sampling necessary to separate turbulent and surface wave velocities at this wave-exposed site.

A set of turbulence data containing temporally well-resolved fields was collected at the Long-term Ecosystem Observatory (LEO-15) off the coast of New Jersey. These data suggest that Langmuir supercells—Langmuir circulations that achieve vertical scales equal to the water depth under extended storms (Gargett et al., 2004)—are a dominant mechanism for major sediment resuspension, hence sediment transport, on the extensive shallow shelves off the eastern U.S. coast. These data also raise fascinating questions about the possible role(s) played by supercells in air-sea gas fluxes, cross-shelf transports, and benthic community structure in these and other shallow seas.

The LEO-15 turbulence experiment consisted of mounting a "turbulence" (5-beam) Acoustic Doppler Current Profiler (VADCP) on a stable bottom platform near one of the observatory nodes. Cabled to shore through the node, the VADCP returned real-time water column velocity profiles roughly every second from April 15 to October 31 2003. After adjustment so that the upward-looking fifth beam was accurately vertical, the VADCP provided unambiguous measurement of vertical velocity (w) from the transducer face, ~1 m above the seabed, right up to the sea surface. Standard slant-beam pairs provided estimates of horizontal velocity components, subject to the usual filtering effect of beam spread and loss of near-surface data through sidelobe contamination. The deployment spanned the full annual range of water-column stability, tidal and atmospheric forcing, as well as passage of a hurricane, so the data set includes the full suite of turbulence-generating processes at the site.

The example shown in the figure was recorded during a typical "nor-easter" storm that lasted for two days in May. The vertical beam backscatter field (A) shows regions of high near-surface backscatter associated with the downwelling limbs (green/blue in the w field) of Langmuir cells, signatures well known to arise from microbubbles of air deposited in the near-surface layer by wave-breaking events, then redistributed to depth by Langmuir circulation (Zedel and Farmer, 1991). Here, however, the backscatter field also reveals clouds of high backscatter originating from the bottom, interpreted as sediment being transported through full water column depth in the upward-going limbs (yellow/red in the w field) of the Langmuir cells.

Acknowledgements: The VADCP observations at LEO-15 were supported by NSF (OCE-0136403) and NOAA (NA06RU0139) grants to Ann Gargett.

Table K-3. Decadal Questions Requiring ORION Infrastructure
How do local shelf and slope changes relate to both surface forcing and water mass anomalies occurring over the continental shelf further upstream (to the north)?
How do changes in the northeast relate to decadal signals in the subpolar gyre, including large-scale wind stress curl patterns and open ocean heat fluxes?
How do decadal signals alter the stratification over the continental shelf and slope and affect the ecosystems and biogeochemistry?
How do decadal trends affect lateral inputs onto the continental shelf, including estuarine/riverine and slope water intrusions, and what is the impact of decadal modulation of these lateral inputs on the ecosystem and biogeochemistry?

inputs onto the shelf from the North, (2) in the middle of the broad MAB shelf (Figure K-1), and (3) at the southern edge of the shelf. Shelf water entering the MAB flows from the southern flank of Georges Bank and the western Gulf of Maine east of Nantucket. Along the offshore boundary, various processes at the shelf break front contribute to exchange between shelf and slope waters (Loder et al., 1998) and to enhanced biological production (e.g., Marra et al. 1990). The Endurance lines would provide time series of temperature, salinity, currents, nutrients, inherent optical properties, and fish acoustics as standard *in situ* measurements. These time series can then be combined with individual PI measurements recorded by new sensors. These subsurface time series should be combined with surface spatial maps of surface currents and satellite imagery.

Process studies to constrain material fluxes at the margins of the shelf would be conducted with Pioneer arrays. Initial Pioneer array studies were suggested to characterize buoyant plumes and the shelf-slope exchange processes. The shelf-slope front separates relatively cool fresh shelf water from warmer, more-saline slope waters. Along this front is a highly variable current with downstream velocities on the order of 0.2 to 0.5 m/s. The variability of this front is so large that its structure has been difficult to ascertain, but it is precisely this variability that makes exchange across the front and productivity along it so important to the MAB ecosystem. Shelf-slope exchange is poorly known and not quantified, despite the long-held view that slope water inputs of nutrients across the shelf break are important for shelf productivity and ecosystem dynamics. These Pioneer arrays would consist of moorings and long-duration autonomous vehicles to provide subsurface spatial data. The inputs from rivers should also be assessed by Pioneer process studies, as the shelf water that flows southward along the coast is impacted by inputs of freshwater, nutrients, and contaminants that enter the shelf via a number of major rivers and bays. It is recommended that core Pioneer measurements should be the same as the Endurance lines. Combined, these measurements would enable 3-D numerical models to assess the coupling among continental shelf physics, sediments, chemistry, and biology. Data assimilating models will enable scientists to optimize the observational arrays.

Instrument and Sensor Technology

Physical oceanographers have a suite of mature ocean sensors that are easily adapted for observatory deployments (e.g., CTD, ADCP). Chemical oceanographers have laboratory and specialized/delicate sensors that will need to be modified and tested for long-term deployment on observatories. Research into more advanced anti-fouling techniques for optical and chemical sensors is a high priority. Biological oceanographers are significantly behind both physical and chemical oceanographers in terms of sensor development. A major effort is required to advance biological sensor technology up to the standards of physical oceanographic sensors. The use of acoustics and video may be initial avenues of pursuit.

Autonomous and Lagrangian Platforms and Sensors (ALPS) will be key components to a coastal observatory, providing essential spatial mapping and event detection. Remote programming and command and control of fleets of "flyers," both in the water and above will allow researchers to "respond" to events detected by moored sensors. Sensors on ALPS will include all disciplines (physical, chemical, and bio-

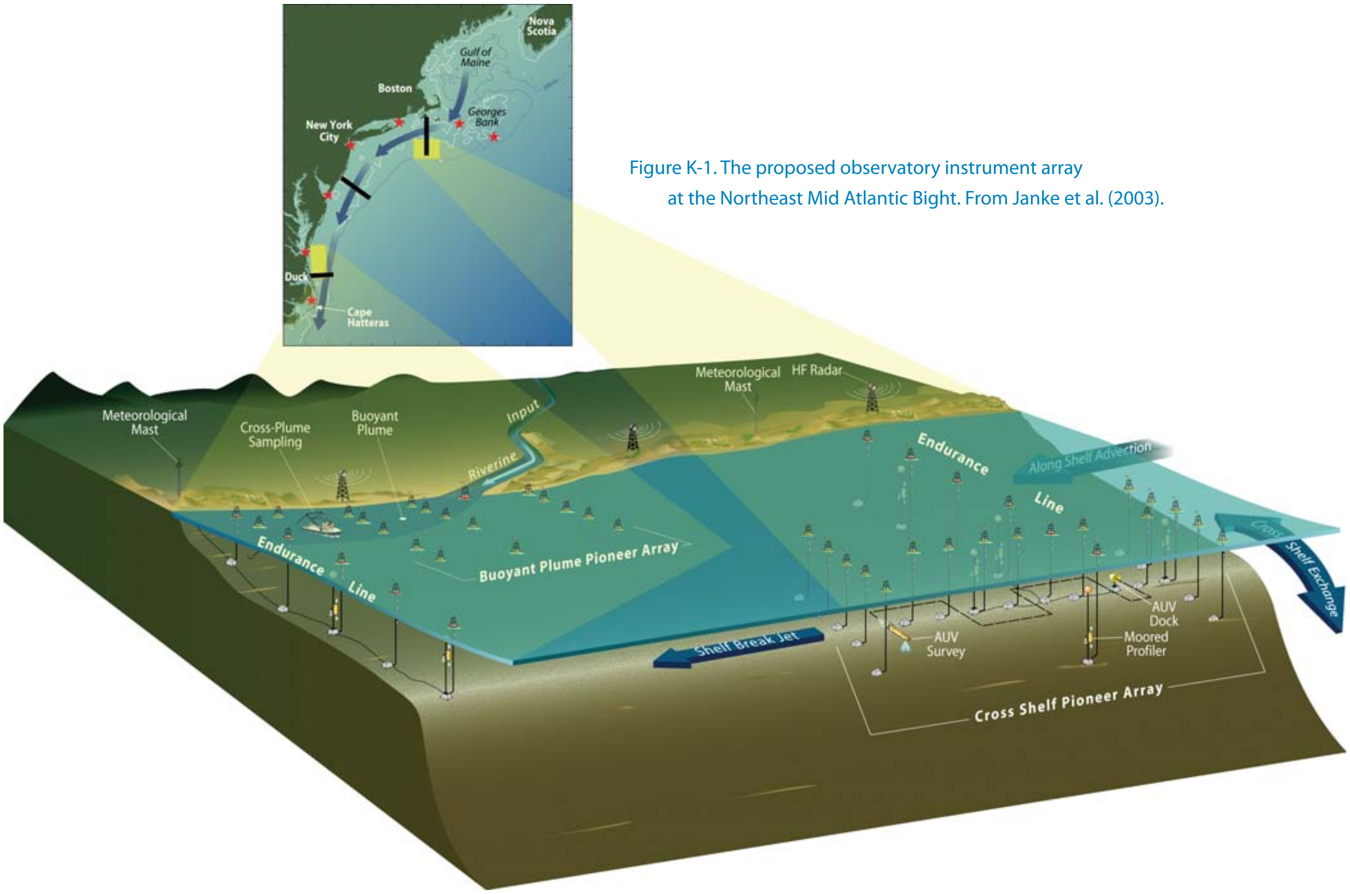


Figure K-1. The proposed observatory instrument array at the Northeast Mid Atlantic Bight. From Janke et al. (2003).

logical). Observatories with Eulerian data alone will limit and frustrate our ability to take advantage of the real-time, data from the observatory.

Exciting new sensors that are under development include bio-acoustic absorption spectroscopy (Figure K-2); phytoplankton identification sensors on AUVs (flow cytometers, FlowCam, HPLC, fluorescence, excitation/emission fluorescence); bar-coded fish tags; other smart sensor tags that record environmental variables as well as position; and feature-tracking devices.

Education and Outreach

The coastal ocean is engaging to the public—even for audiences in non-coastal states. Harmful algal blooms, storms, winds, and waves are of widespread interest. Data acquired by ORION need to be converted into "information products," and there need to be "portals" created to take these products to the public. Centers for Ocean Sciences Education Excellence (COSEE) could serve this purpose, particularly for educators and students. Displays at museums and aquaria would reach the non-formal education audiences. Television and radio "ocean weather" reports would also be a means of broadcasting results. All of this will require dedicated personnel such as scientists, educators, and other user groups, and adequate funding.

The goal for education should be to change how students view science from "science is something that is done by others for you to learn about" to "science is something that is happening now that you can participate in." Education materials should emphasize what scientists don't know as much as what they do know, because the mysteries of science are often more compelling than learning a collection of facts or rules. However, care must be taken not to give the idea that well-accepted facts are subject to varying interpretations.

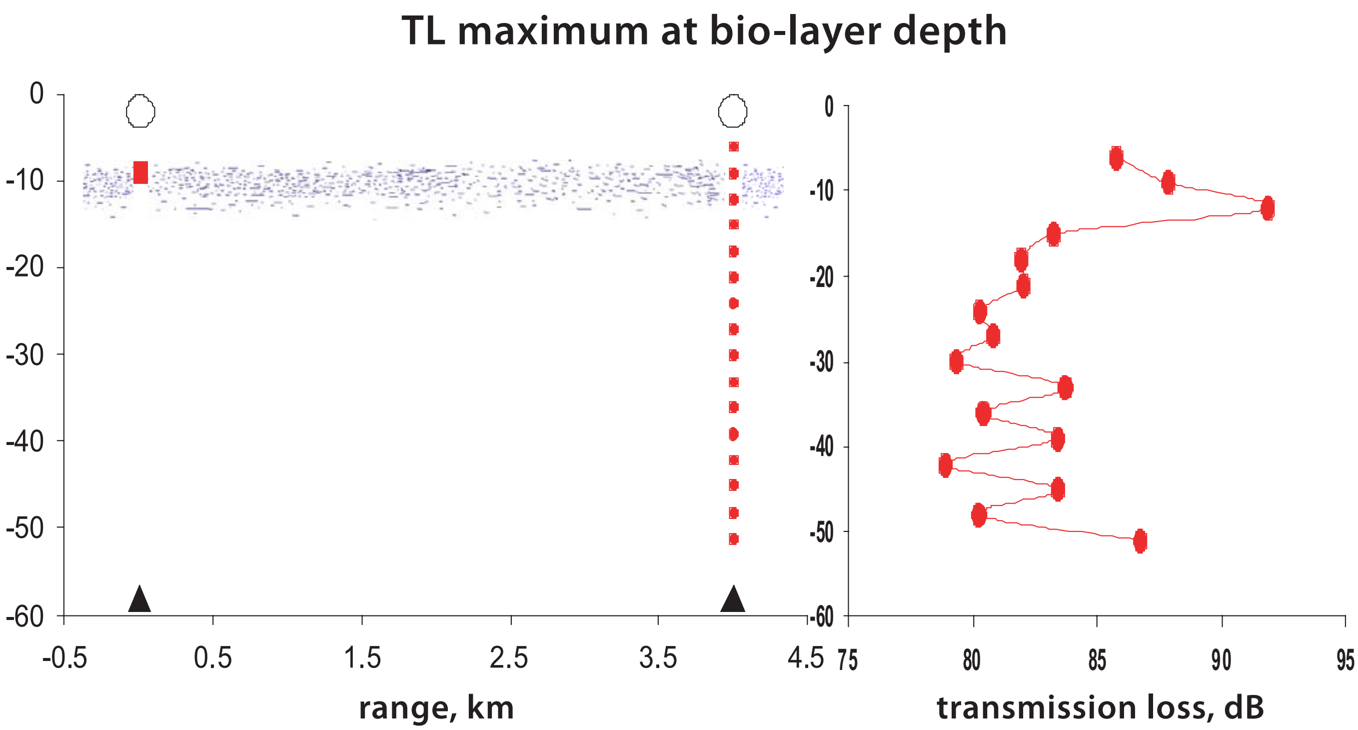


Figure K-2. Left: broadband (0.25-10 kHz) source, receiving array and bio-absorbing layer at night. Right: Transmission Loss (TL) vs depth at 1.2 kHz, the resonance frequency of 15 cm sardines at 14 m. Figure courtesy of Orest Diachok, Poseidon Sound, and University of Washington Applied Physics Laboratory.

ORION should develop an inexpensive "tool box" to enable students to design their own observing system (e.g., engage in shore-based sampling programs) and provide them with computer models and data. Working with scientists, data, and models can be used in curricula development. Data mining over the Internet is an easily implemented inquiry-based activity (e.g., coastal ocean temperatures), but teachers need training to learn about the availability of data archives and how to access them. Training should be provided to pre-service (undergrad) teachers as well as to practicing teachers. There should be plenty of follow-up with teachers after formal training sessions (e.g., summer workshops). Follow-up would include occasional meetings to get teachers together during the school year following a summer workshop, and email and telephone assistance to answer questions that arise throughout the year. Successful activities should be presented at National Science Teacher Associate conferences and other such venues. Activities should be peer-reviewed by scientists and educators for accuracy and effectiveness.

A major concern is that academic scientists who participate in outreach and education activities are often not recognized or rewarded (e.g., when promotion and tenure decisions are made). There should be a cultural shift to value these activities. Can NSF play a role in this?

Miscellaneous Concerns, Issues, and Recommendations

1. We need to understand processes well enough to make predictions of the ocean state (or other variables) when forcings are outside the range of conditions experienced to date.
2. ORION should be concerned with models (ocean and atmosphere) as well as observations.
3. Observatories need to get the atmospheric forcing right (e.g., solar radiation and wind stress).
4. NSF should expect that observatories will require enhanced UNOLS support to maintain assets.

5. Observatories can be used for remote sensing calibration/validation (salinity to 0.1 psu, SST via all-weather microwave methods, altimetry and winds at higher resolution than currently available, optical sensors for color—for example, MOBY).
6. Aircraft are potential "facilities" (sample marine boundary layer, test new remote sensing techniques and sensors, deploy instruments, and provide better spatial resolution than satellites).
7. The information management related to integrating data from this diverse network of observatories is an enormous challenge. It will take about 80% of the effort to keep up with data flow and meet user demands. Meanwhile, the remaining 20% should be devoted to a parallel effort to develop state-of-the-art prototype data management and communication systems, and feed these into the operational system so the latter doesn't "fossilize."
8. Coastal observatories will be driven by issues important to the public, for example, HABs and pollution. Successful solutions—visible to the public—will help sustain ORION.
9. Observatories will need to have an open data policy.
10. There will be a need for thoughtful and integrated QA process.
11. ORION should provide opportunities to entrain the broader scientific community.
12. There is a need for short-term, mid-term, and long-term successes.

Continental Shelves Working Group

- Antonio Baptista, Oregon Health and Science University
- Jack Barth, Oregon State University
- Bob Beardsley, Woods Hole Oceanographic Institution
- Trisha Bergmann, University of Maine
- Emmanuel Boss, University of Maine
- Ken Brink, Woods Hole Oceanographic Institution
- Annette deCharron, Bigelow Laboratory for Ocean Sciences
- Richard Dewey, University of Victoria
- Janet Campbell, University of New Hampshire
- Amy Cline, University of New Hampshire
- Curtiss Davis, Naval Research Laboratory
- Orest Diachok, Naval Research Laboratory
- Paul DiGiacomo, NASA
- Scott Gallager, Woods Hole Oceanographic Institution
- Glen Gawarkiewicz, Woods Hole Oceanographic Institution
- Scott Glenn, Rutgers University
- Dale Haidvogel, Rutgers University
- Amy Holt-Cline, University of New Hampshire
- Rick Jahnke, Skidaway Institute of Oceanography
- Barbara Kirkpatrick, Mote Marine Laboratory
- Gary Kirkpatrick, Mote Marine Laboratory
- Dave Maier, Oregon Health and Science University
- Dave Martin, APL University of Washington
- Carrie McDougall, NOAA Office of Education
- Maia McGuire, Florida Sea Grant
- John Moisan, NASA Goddard SFC
- Steve Morey, Florida State University
- Ru Morrison, University of New Hampshire
- Christina Orrico, University of California, Santa Barbara
- Neil Pettigrew, University of Maine
- Jay Pinckney, Texas A&M University
- John Pompa, Scripps Institute of Oceanography
- Antonietta Quigg, Texas A&M University
- Tammi Richardson, Texas A&M University
- Collin Roesler, Bigelow Laboratory for Ocean Sciences
- Dan Rudnick, Scripps Institution of Oceanography
- Dana Savidge, Skidaway Institute of Oceanography
- Tim Shaw, University of South Carolina
- Larry Smarr, University of California, San Diego
- Heidi Sosik, Woods Hole Oceanographic Institution
- Lundie Spence, SC Sea Grant Consortium
- Chuck Trees, NASA
- Bob Vaillancourt, Lamont-Doherty Earth Observatory
- Amos Winter, National Science Foundation

L. Small-Scale Mixing and Nearshore Processes

James O'Donnell (Moderator), Rocky Geyer (Moderator), Falk Feddersen (Rapporteur)

Most people interact with the ocean at the edges. Recreation, transportation, fishing, and waste disposal are all concentrated at our coasts. Pollution created by these activities is subsequently carried into the ocean and mixed. Where the effluent goes and how it is transformed is central to predicting its consequences and valuing its impact. Vertical mixing also controls the concentration of nutrients in the ocean, so understanding the spatial structure and variability of coastal ocean productivity will be impossible until we improve our understanding of mixing. The ocean also affects the land. Severe ocean storms erode beaches, damage coastal infrastructure, and transport sediment into navigation channels. Development of integrated management policies for the coastal environment that allow both the preservation and use of marine resources is dependent on understanding the shallow, nearshore interface between land and ocean. The quantitative prediction of vertical mixing in the coastal ocean is historically based on a competition between the local production of turbulence by shear and its dissipation through mixing and friction at the same place. Recent work suggests that many important hydrographic features (salinity field and vertical structure of the phase of tidal currents) cannot be understood unless a non-local source of mixing is included. For example, momentum generated from internal waves out on the continental shelf influences local mixing processes in the nearshore environment. Unraveling this issue is central to understanding mixing processes and subsequent transformation of material in the nearshore coastal ocean. Assessing the interaction between local and mesoscale processes is a challenging problem.

ORION will provide the infrastructure necessary to support biological, chemical, and physical measurements that require high bandwidth and power for sustained periods of time. The infrastructure will sample as sufficiently high frequencies to resolve both short-lived episodic events and low-frequency global processes that can dramatically impact nearshore coastal environments. Such measurements are particularly important for nearshore environments, which are highly turbulent and difficult to sample.

Scientific Priorities

1. Gain a predictive understanding of the occurrence and spatial structure of vertical mixing on the shelf.
2. Gain a predictive understanding of particle aggregation/disaggregation, the dispersion of larvae, the ecology of fish, and the influence of turbulence and mixing on productivity.
3. Gain a predictive understanding of turbulence in the surf zone resulting from long-shore currents, and the role of long-shore currents in morphological transformations.

The working group on Small-Scale Mixing and Nearshore Processes identified two critical areas of research in which the ORION infrastructure will be central: mixing and morphodynamics. These two topics share a common theme—the linking of disparate spatial and temporal scales. ORION will provide comprehensive ocean-observing capabilities, including sufficient power and bandwidth, capable of collecting and transmitting data required to tackle these important problems. Spatial data collected at very high sampling rates will allow focused study of multiple experimental sites over a range of physical forcing scenarios.

Example ORION Experiments

Mixing: where, why and when?

Until recently, the theoretical basis for the quantitative prediction of vertical mixing in the coastal ocean has relied upon a competition between the local production of turbulence by shear and its dissipation through mixing and friction at the same place. There have been a few field experiments that have tested this idea by direct measurement of production and dissipation rates, and they have shown the formulation works quite well; however, there have also been many studies that showed that the salinity field and vertical structure of the phase of tidal currents in the coastal ocean can't be simulated realistically unless there is a source of mixing that is not associated with the shear at the scales simulated by the model. For example, a parameterization of internal wave activity is necessary to align model results and observations of mixing dissipation rate. This "fix" recognizes that there are unresolved processes and scales that generate internal waves that propagate momentum from elsewhere. Though this is a well-understood limitation, to improve our predictive capability we need a way to link the effect (enhanced dissipation) with the mechanisms that initiate and propagate the high-frequency internal motions.

Even when the vertical flux of heat and salt is as assumed by well-established models, the location of the large fluxes moves around. For example, in agreement with the theoretical studies, the response of a buoyant coastal current to an upwelling-favorable wind is for the offshore front to move across the shelf (Figure L-1). Consequently, the buoyant layer thins and mixes vertically. This mechanism of across-shelf transport of terrestrial runoff may be very important. Whether it actually happens in nature is unknown at the moment. But it is clear that observing the phenomena presents difficult challenges because the location of the mixing moves, it is near surface, and is likely to occur during high-wind conditions.

ORION will provide a nested grid of observations spanning the nearshore coastal environment and the outer continental shelf. Because mixing is intermittent and occurs at very small scales (0.01 to 10 m), frequent dense-sustained measurements of velocity, temperature, and salinity are required to capture the full range of variability. Linking the effect to the cause requires contemporaneous observations over spatial scales of tens to hundreds of kilometers so that propagation can be observed and sources identified. Additionally, high-resolution measurements in regions of internal wave generation will be necessary in addition to acoustic tracking of their propagation.

Much of the technology needed to understand the spatial structure and variability in mixing exists. However, the need to coordinate observations at both small and large scales, and the magnitude of the investment in infrastructure required, has limited its application. Acoustic Doppler profilers are capable of making the necessary measurements of velocity though deployments, but have been limited by power and data telemetry constraints. Complementary measurements of microstructure have been acquired by ship-launched profiler and towed arrays and are being tested on ROVs and moored profilers.

Fundamental understanding of mixing could be greatly advanced by ORION, providing measurements from the shelf-break fronts, to coastal currents, all the way into the surf zone. These measurements made over sustained periods of time will provide context for larger-scale processes that also impact local mixing processes. Although ORION is the ideal venue for a comprehensive study of vertical mixing in the coastal ocean, the most far-reaching impact of ORION will be the opportunity to coordinate the study of the causes and consequences of vertical mixing with observations of the impact on biological processes of the coastal ocean.

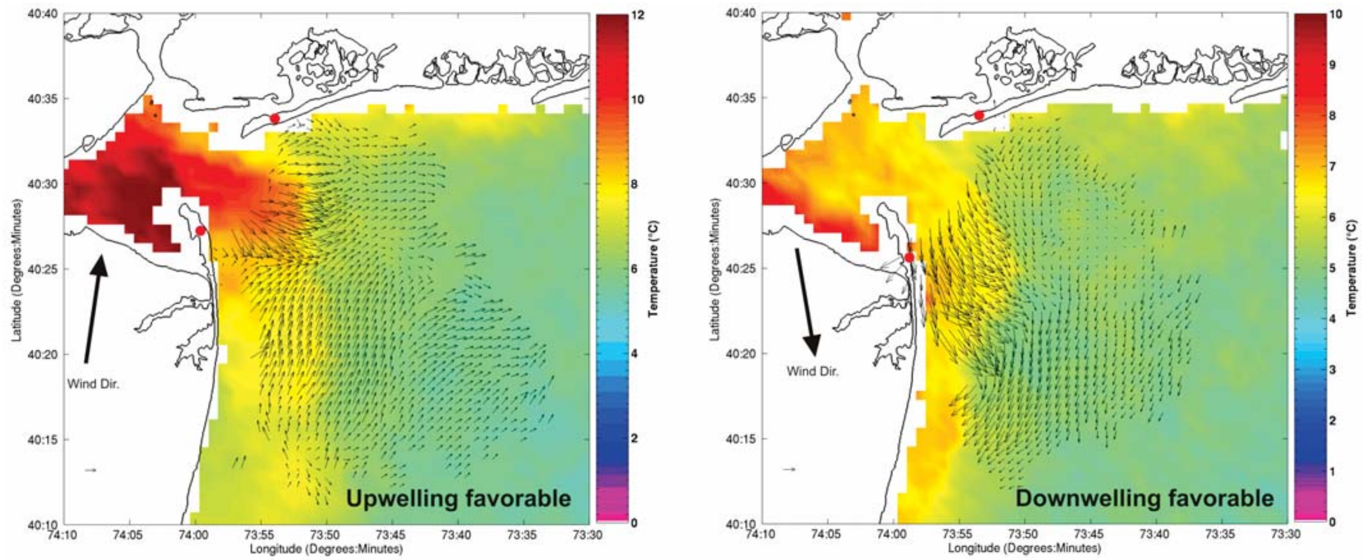


Figure L-1. The response of the Hudson River plume during upwelling and downwelling favorable winds. The vectors are measured with a HF CODAR system, and the sea surface temperature was measured AVHRR satellite imagery. As predicted by theory the buoyant plume flows out over the shelf to the north during upwelling favorable winds. In contrast the downwelling winds leads to a tight southerly flowing coastal jet along the New Jersey coast.

How do waves impact our coastlines?

Ocean margins subject to high waves can experience substantial morphological changes during storms. There are areas where the shore is receding, endangering buildings and highways. These changes can be caused by either extreme events, persistent wave conditions, or both. Understanding the relationships between the generation of waves and their impact on shorelines is presently very limited. Useful predictive models do not yet exist. ORION presents the opportunity to develop and sustain a network of instruments that can establish the relative importance of the variety of mechanisms that control coastal evolution. The data set resulting from the experiment will provide a valuable underpinning for effective predictive models.

Understanding morphodynamics requires the augmentation of an ORION shelf array that observes the structure of the current, wind distributions, and directional wave spectra with arrays of instruments in the nearshore (within 1 km or < 10 m depth). The shallow array of perhaps 20 tripods/towers must extend across a complete littoral cell to complete sediment budgets, and observe erosion, transport, and deposition. These instrument arrays should measure the vertical and horizontal distribution of velocity, temperature, conductivity, and sediment concentration at a vertical resolution of 50 cm. This instrumentation will facilitate vertical mixing and turbulence studies in the nearshore region that complement those in deeper shelf waters discussed earlier. The along-shore spacing should be capable of resolving the topography and the wavelengths of shore-trapped waves. Lagrangian drifters and remote-sensing techniques, particularly X-band radar, and video methods, are likely to complement these observations.

A long (perhaps a decade) deployment will be required to capture the response to both severe storms and slow changes. Rugged instrument packages must be developed. New approaches for their deployment in the surf zone will also be necessary if the most energetic areas are to be studied. Repeated surveys of the bathymetry and coastline shape will be required to complement observations of erosion, deposition, and transport rates. To separate slow changes from the response to extreme events, the schedule must be adaptable and surveys rapid. LIDAR-based remote-sensing techniques and jet-ski-based acoustic surveys show promise; however, new techniques for *in situ* mapping and sediment sampling/coring during extreme events are also needed. Bottom crawlers should be considered.

Working Group Members

Larry Atkinson, Ocean.US/Old Dominion University
Mohsen Badiey, University of Delaware
Steven Colman, U.S. Geological Survey
Manhar Dhanak, Florida Atlantic University
Tom Drake, North Carolina State University
Falk Feddersen, Scripps Institution of Oceanography
Rocky Geyer, Woods Hole Oceanographic Institution
Hosni Ghedira, NOAA
Tom Herrington, Stevens Institute of Technology
David Kohler, Florida Environmental Research Institute
Mike Kosro, Oregon State University
Jacques Locat, Laval University
Ru Morrison, University of New Hampshire
James O'Donnell, University of Connecticut
Joan Oltman-Shay, North West Research Associates
Richard Seymour, Scripps Institution of Oceanography
Eric Terrill, Scripps Institution of Oceanography
Judith Wells, Old Dominion University
Don Wright, Virginia Institute of Marine Science

IV. Technology

Jim Bellingham (Moderator/Rapporteur)

Physical Infrastructure of Next Generation Ocean Observing Systems

The ORION initiative builds on advances in fields such as subsea cable technology, satellite communications, and mooring design, and is enabled by world-wide connectivity of the Internet. The potential and challenges of creating regional-scale cabled observatories, coastal observatories, and global mooring arrays are discussed extensively in a variety of reports (e.g., National Research Council, 2000; Glenn and Dickey, 2003; Jahnke et al., 2002; National Research Council, 2003; Detrick et al., 2000). Although it is clear that many of the enabling technical advances originate from outside oceanography, it is equally clear that the creation of the ocean observatory infrastructure is more than just a straightforward application of existing technologies. The mooring arrays envisioned for the coastal Pioneer arrays and Endurance lines involve more individual moorings and instruments than any prior mooring arrays. The global mooring system requires power and communication connectivity from the surface to the seafloor with reliability that is hard to guarantee with the existing state of the art. The regional-scale cabled observatory uses telecommunications cables in a way never envisioned by the telecommunications community, to support networks of instruments on the seafloor.

In many respects, ORION's engineering goals can be summarized as follows: to make ocean observations easier to sustain, and make the resulting data more broadly accessible. In recent years, advances in sensors, platforms, and computational tools such as assimilative ocean models have been dramatic. However, for the most part, such systems are accessible only to the developers. For some technologies, for example, for autonomous underwater vehicles (AUVs), which have been commercialized, participation is somewhat more flexible, extending to scientists willing to take on the burden of maintaining a technical team capable of operating and maintaining the vehicles and their instruments. The ORION effort seeks to lower the threshold for participation by taking two key steps. First, create an infrastructure to provide power and communications for widely distributed *in situ* instrumentation. Second, have the resulting facility take at least partial responsibility for community instruments and make data easily accessible. The vision is to engage a broad range of scientists, from those who develop instrumentation and carry out complex experiments in the ocean, to those who engage in discovery through interaction and manipulation of oceanographic data sets and databases.

Although the objective is to enable the individual PI, creating the infrastructure to accomplish this goal is a large undertaking. The scale of the ORION infrastructure makes formal engineering practices essential. Management structures must provide for such activities as: gathering science needs to drive system design, developing and vetting initial functional requirements, deriving system specifications from functional requirements, reviewing system and subsystem designs at various stages of maturity, ensuring designs and fabricated elements meet system specifications, developing training and operational procedures, and more. The large number of activities involved in a project of this scale makes project management a critical ingredient for project success. The challenge of translating desired functionality into quantitative system performance specifications, and ensuring designs satisfy those performance specifications, elevates system engineering to a central role in the enterprise.

A particular challenge in the development of large scientific systems is ensuring that science needs are clearly represented to the engineers who are designing and building the system. A substantial up-front investment is needed to derive what are called the "functional requirements," which are the statement of what functions the users (in this case the scientists) wish the system to perform. However, the uniqueness of the observatory systems makes such projections particularly difficult. The designers of new ocean-observing systems must anticipate patterns of science use to ensure the resulting infrastructure can support science that has yet to be imagined. Although new and unexpected ways to take advantage of the infrastructure will undoubtedly emerge, a detailed planning process that anticipates patterns of use is clearly a worthwhile investment. Such a process requires developing scenarios for science use of the system, with the value of the exercise being notionally proportional to the level of detail and realism in the scenarios. Such a process is just the beginning of science input into the design process, and virtually all "large science" activities have a chief scientist continuously engaged with the engineering team to ensure priorities remain balanced, and to provide science guidance for resolving inevitable conflicts that will arise.

The particle physics community is often held up as the prototypical "big science" discipline, and the history of large system developments carried out by this community provides a rich source of lessons. Galison's case study of the development of the Time Projection Chamber (TPC) provides insight into the challenges of the science-engineering interaction and the evolving roles of each in big science activities (Gallison, 1997). The TPC is a device that allows the three-dimensional reconstruction of many charged particle paths through a volume simultaneously, an essential capability when high-energy collisions produce many secondary particles. What made the development of the initial TPC challenging was, unlike most earlier large-scale high-energy physics projects, the engineering and physics could not be easily separated into distinct elements of the project. Furthermore, the complexity of the project made it impossible for any one individual to encompass all the key elements. Jay Marx, a physicist, who served as project manager for a significant period, articulated his lessons learned, "…THE INTERACTION BETWEEN ENGINEERS AND PHYSICISTS IS CRUCIAL. Leave an adequate R&D phase in the beginning where the specifications and cost tradeoffs can be argued by physicists and engineers. These debates should be aggressive and forthright." (Gallison, 1997, p. 623). Other important lessons revolved around the need for engineers to understand the science drivers, and for physicists to understand engineering processes.

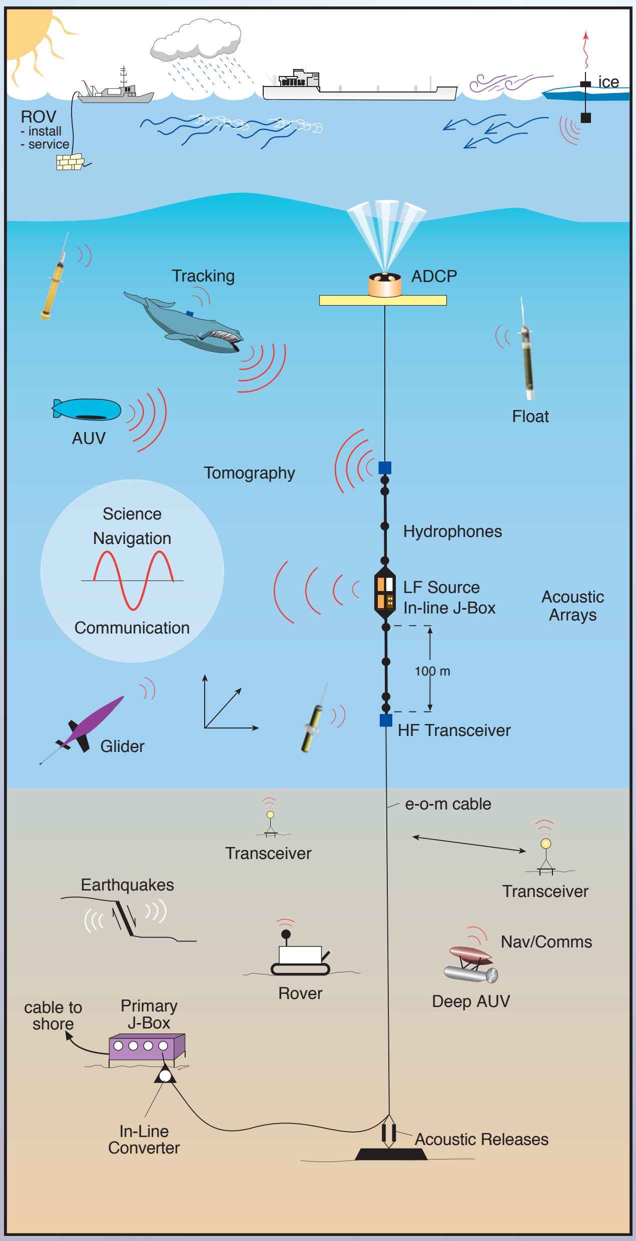
The success of ORION depends on achieving close and productive collaborations among many normally weakly interacting communities. Oceanographers from a wide variety of disciplines must agree on the fundamental needs driving the creation of next generation ocean-observing systems. Technologists from a wide array of disciplines will be called on to create new capabilities to enable the physical infrastructure, new instrumentation, and the cyberinfrastructure that binds the elements into a whole. Engineers will apply existing and new technologies to create the large systems that will be the enabling elements of ORION. Academic, government, and commercial organizations will all play essential roles. To succeed, we will need to attract and retain the best talents in all these domains. This requires an atmosphere of partnership, built on mutual understanding, respect and trust. The GEMINI telescope program confronted challenges reaching such synergy early in its history, and as a response adopted the "General Principles for Gemini Partner Interactions." We suggest the ORION community consider discussing and articulating its' principles.

Establishment of testbeds for the observatory program provides a way to develop experience with observatories on a smaller scale before committing to the design of the full-scale systems. Such testbeds not only allow testing of technical elements of the observatory, but by enabling the development of an "observatory user community," build an experience base which will be invaluable for informing the science needs and functional requirements for the larger systems. The regional-scale cable observatory has two testbeds: the NSF-funded US testbed is MARS, while the testbed for the Canadian NEPTUNE program is VENUS. Further, the ~6 node regional-scale cabled observatory being installed by NEPTUNE Canada can be regarded as a testbed for the subsequent larger US regional-scale cabled observatory. The coastal networks have mature test-beds such as the Long-term Ecosystem Observatory (LEO-15) and the Martha's Vineyard Observatory, which have already anchored many large science process studies.

Box 11 Integrating Acoustics into Ocean Observatories

Contributed by Bruce Howe, University of Washington, and Jim Miller, University of Rhode Island

Integrated acoustics systems are critical and essential elements of ocean observatories. Acoustics provide an efficient and cost-effective means by which physical, chemical, biological, and geological parameters and processes can be measured and information communicated. We use acoustics because the ocean is opaque to electromagnetic waves, but is largely transparent to sound, permitting synoptic observation of ocean volumes. For ORION, a series of nested systems is envisioned, from small- to regional- to basin-scale. At these scales, a small number of acoustic sources sending coded, low-power signals can service unlimited numbers of inexpensive receivers (see figure). Mobile, moored, and fixed receivers can navigate accurately while enabling data collection on:



- acoustic tomography; ocean temperature and absolute velocity measurements can provide ocean dynamics, circulation, and heat content information
- ambient noise associated with wind and rain fall; spectral signatures of underwater sound generated by these processes are distinctive, allowing for their measurement and contributing to the study of related processes such as gas transfer
- marine animals and their activity; marine mammal vocalizations and active tracking can be used for species identification, abundance and behavioral studies
- seismic T-phase monitoring; hydroacoustic monitoring of T-phase arrivals can be used to detect weak seismic events and underwater volcanoes
- anthropogenic activity in the oceans.

Understanding the behavior of nekton, from krill to blue whales, will be greatly facilitated using active and passive acoustics for tracking and imaging, likely with various mobile platforms involved. Other uses of acoustics include: hydrophone-equipped, precisely geo-referenced floats (e.g., Argo, RAFOS) that provide direct velocity estimates, ambient sound data, and serve as moving tomography receivers for ocean temperature estimation between the point-float locations and sources; seafloor geodesy and tomography/imaging around hot vent, methane hydrate, and other sites of geologic and biological interest; navigation and communication with AUV fleets conducting benthic and full water column survey over all scales; and bottom or moored general purpose acoustic multi-beam sonars (next generation ADCPs/"weather radars") sensing velocity and biology as well as serving as directional navigation beacons and communication modems. Many of these applications can share the same equipment that is robust, long-lived, and calibration-insensitive—characteristics essential for sustained ocean observation.

Instrumentation

The power, communication, and timing infrastructure of new observatories effectively opens the door to the deployment of more-complex, more-power-intensive devices than can presently be routinely deployed in the ocean. Further, the distributed nature of ORION provides the ability to make simultaneous observations in widely distributed parts of the ocean. Consequently, although the opportunities for instrument developers to create new classes of ocean instruments has never been greater, the demands of ensuring those instruments are calibrated, reliable, and openly available are significant.

What sorts of instruments will the availability of abundant power and continuous connectivity enable, and how will scientists interact with them? The borehole experiments described by the Fluid-Rock Interaction and Its Influence on Life Working Group illuminate some of the possibilities. The geohazards posed by gas hydrate decomposition would be investigated by an experiment in which heating elements were used to heat hydrates and the effects on the surrounding seafloor monitored for a period of a year. Pumps for sampling fluids from nearby boreholes would be employed in addition to a variety of sensors. Such an experiment is possible only within an infrastructure that can provide substantial power over the extended period; having a high-bandwidth communication link would make chances of success much higher. Looking to the future, one might expect *in situ* experiments to be a significant ORION activity, and early scientific interest for the MARS cabled observatory seems to confirm this.

At the MARS User Meeting at the December AGU Conference, eight proposed activities were outlined (see http://www.mbari.org/mars/new/presentations.html#MARS%20Users%20Group%20Meeting). One of those was a benthic lander, which is accompanied by three benthic crawlers (see http://www.mbari.org/mars/pdfs/LorenzAGU.pdf). One of the crawlers, which carries a variety of sensors, is already assembled and operating in a test tank in Germany. Design of this system took maximum advantage of a high-bandwidth link, using Internet capable actuators and sensors to eliminate the need for onboard intelligence. The interface to the crawler is a web page, which among other items, displays images from a still camera. Experiment options unavailable with a fully autonomous system are possible. One simple example: a scientist can choose the location on the bottom for the benthic chamber experiment. Construction of the crawler took four months. This vignette suggests the possibilities: by assuming human supervision or shore-side computation, the *in situ* hardware can be simplified dramatically while increasing flexibility. By drawing power from a cable, restrictions on hardware selection driven by power management are greatly relaxed, as compared to battery-operated systems. These two factors should allow the oceanographic community to expand from passive observation and sampling, to direct *in situ* analysis and experimentation.

Certain ORION activities are driven by the need for spatially distributed measurements. For example, the Earth Structure working group outlines the need for filling in the global coverage of seismic stations, especially in the southern hemisphere where there are few oceanic islands. This is an example of an activity where ORION will need proven instrument designs that can be replicated in quantity, deployed and operated reliably by staff other than those who designed it, that are designed to connect to the infrastructure, and that produce data and metadata which can be readily archived and incorporated into databases. Because instrument development is expected to be a significant activity, review processes for verifying instrument designs and functionality of supporting data archiving and accessing systems prior to full deployment will be necessary.

Distributed observations of the water column are more complex, often requiring a heterogeneous mix of observational assets, for example moorings, drifters, and mobile platforms. AUVs can provide dense, *in situ* measurements that cannot be obtained via a fixed infrastructure, and largely for this reason, half of the ORION scientific working groups identified AUVs as an important observatory element. The spacing of seafloor observatory nodes, whether elements of a global mooring array or distributed on the backbone of a regional-scale cable observatory, will significantly under sample many processes in the spatial domain. Presently, propeller-driven AUVs with physical, chemical, biological, and/or bottom mapping sensors, have endurances on the order of a day or less. A docking capability allows AUVs to draw on the power and communication infrastructure of a seafloor observatory enabling extended, sustained operations of AUVs. However, docking has only been demonstrated as a proof of concept, and is not an operational capability at present. Furthermore, the present generation of AUVs are serviced by humans between operations. Consequently, a high priority for ORION is the development of AUVs and docking systems capable of operating without human presence for extended periods.

Although the instrumentation possibilities afforded by ORION are exciting, a host of challenges must be addressed. For example, who will own, maintain, and operate community instrumentation? Will this be the role of facilities, or of teams of scientists and engineers? Will the traditional individual PI instrument development model be sufficient to create instrumentation for ORION, and if so, how will instruments be transitioned to community use? The concept of a community instrument encompasses several needs. Certain classes of measurements or operations will be common needs of large groups of users, and these should be available to all. Furthermore, instruments that require a significant investment should be designed to satisfy the broadest possible range of users, not just the needs of a single investigator.

The development of community instruments brings a unique set of challenges, as was learned in the Gemini community instrument programs (National Research Council of Canada, Parksville, BC, July 8-9 1999). The construction of the twin 8-m telescopes, one on Mauna Kea and one on Cerro Pachón, were matched by several community instrument-development efforts. The underlying logic was that investment in creating the 8-m telescopes ($184M) demanded an equivalent effort to ensure first-rate instruments. The scale of each of these development efforts was roughly comparable to larger oceanographic instrument programs. As events unfolded, all of the developments were delayed, with not a single community instrument ready to be used when the telescopes became operational. A meeting was held to discuss the lessons learned, with 14 presentations. The central issue raised was the importance of effective project management, with a list of both important and undesirable features identified. Many other topics were discussed including identifying the customer (the Gemini project office rather than the end users, who are too far removed), importance of having the science drivers clearly identified, the need to avoid feature creep, and streamlining contract procedures. Software was a common problem, and one of the solutions identified was to create a standard for instrument development. In short, although community instrument programs are smaller scale than the observatory infrastructure, they need to be taken seriously.

Cyberinfrastructure

The ORION cyberinfrastructure will be the glue that binds the instruments, archives, processing, data discovery, and visualization tools into a seamless whole (see Cyberinfrastructure box on p. 108). While there are important lessons to be learned from the high-energy physics and astronomy experiences, the problems faced by oceanography are unique. Oceanography spans a wide range of disciplines, including such disparate fields as geophysics, physical oceanography, and microbiology. Our sensors operate in a highly hostile environment, and produce results that require expert attention to ensure quality. Our data sets are heterogeneous, including seismic records, satellite observations, video, sonar maps, CTD sections, and genomic databases, to name but a few. We run oceanographic assimilation and modeling systems that require large computing resources. In short, the diversity of science activities likely to be supported under ORION test the limits of current computing and data systems in nearly every sense.

The transformational nature of a well-designed data system has been demonstrated by the recent experience of the astronomical community. Increasingly, principle investigators access their own telescope observations through the same data access systems that archive users employ. The astronomical community has employed cyberinfrastructure for more than improving data accessibility. Remote operation of telescopes, so called “point and click astronomy,” is now a reality (McCray, 2004). Although the new 8-m telescopes fostered a revolution in observational capability, the cyberinfrastructure that developed around the giant telescopes fostered a revolution in the way that astronomers work. The changes may be even more far reaching for the oceanographic community.

The importance of cyberinfrastructure to the success of the ORION enterprise was evident in the ORION meeting. A significant investment in this area is already being made both

Box 12. The Future of Biological and Chemical Sensors in Oceanography

Contributed by Scott M. Gallager, Woods Hole Oceanographic Institution

Oceanographic sensors provide both a projection of human cognitive processes into the remote and often harsh ocean environment, and an extension of human sensory capabilities well beyond our own capacity to detect phenomena of interest. The next generation of sensors will allow scientists to address critical interdisciplinary questions based on long-term, high-resolution measurements of the ocean's biological and chemical properties. Rapid advances in miniaturization, sensor integration, and enhanced embedded computing power through micro and nanotechnology are fueling the development of the next generation of oceanographic sensors.

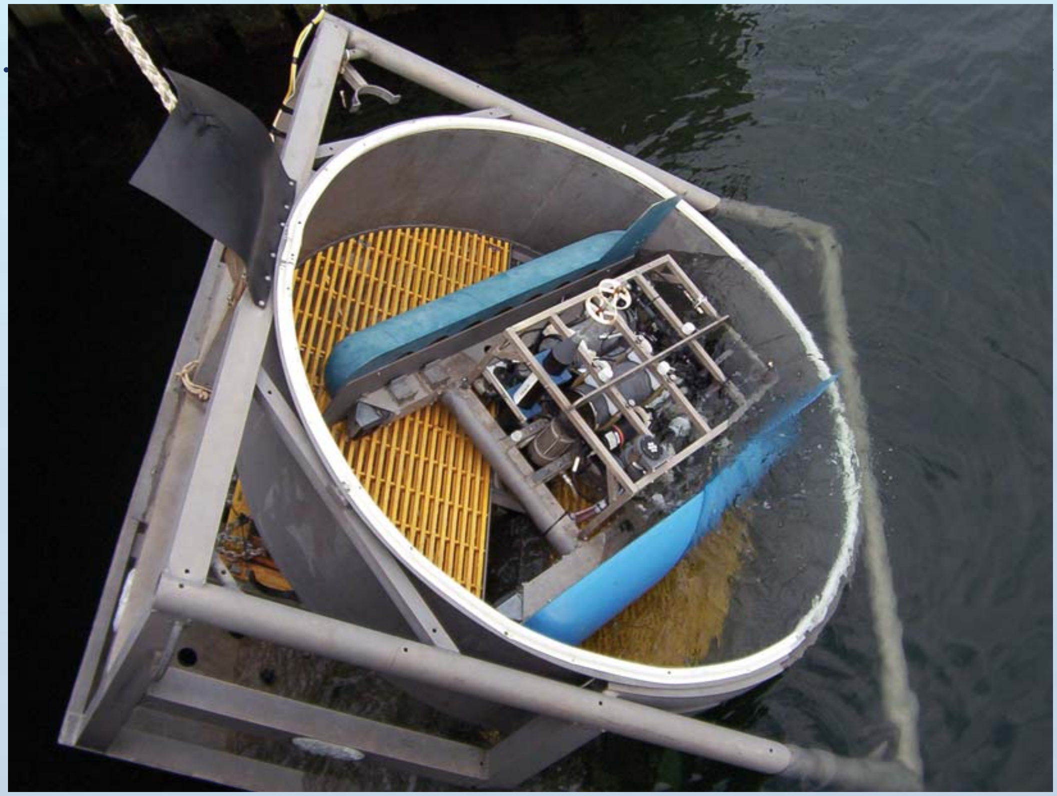
With the use of cabled observatories, autonomous underwater vehicles, and satellite imaging systems, oceanography is entering an era of remote sensing when the oceanographic sensor of tomorrow will need to withstand extended deployments in harsh environments and have a fast response with high accuracy, precision, and wide dynamic range. Exciting advances in sensor development are occurring for *in situ* optical spectrophotometry, mass spectrometry, voltammetry, and laser-induced breakdown spectroscopy (LIBS) for measurement of elemental composition, trace metals, nutrients, and dissolved gases. Novel, nucleic acid sensors for measuring the abundance of specific genes and gene products (DNA, RNA) also show great promise for species identification.

Combining molecular probes with optical imaging and acoustic systems would provide a complete system capable of quantifying a wide range of planktonic organisms. Information on rate processes such as metabolic state, feeding rate, growth rate, and primary and secondary production is also required to complement concentration data. The overall challenge is to develop a capability for predicting the potential for growth and reproduction from proxy measurements of the activity of specific biomolecules like extracellular bacterial enzymes and copepod digestive enzymes. Miniature analytical systems that meet some of these functional requirements are under active development and in some cases are already commercialized for biomedical applications. Bringing these advancements to bear on autonomous platforms applied to environmental research and monitoring requires sample collection and processing schemes that differ from those currently used or envisioned for biomedical tests.

In the near future, small molecular diagnostic devices will probably not provide data rates comparable to chemical and physical measurements, like those possible with conductivity or temperature sensors. Thus, near-term application of biosensors fielded on autonomous platforms will likely be tightly integrated with, and to some extent controlled by, other sensors that trigger a molecular analytical event in response to environmental gradients readily detectable at high frequency.

Cross cutting issues and recommendations

1. Sensor calibration must be established to ensure data quality. Self-calibration procedures are necessary, especially for autonomous sensors on extended deployments.
2. Integration of multiple sensors (i.e., sensor fusion) is required to address specific science questions and/or to reduce engineering requirements or instrument complexity (e.g., sensors requiring pumped sampling could be integrated).
3. Use microfabrication technologies to improve sensor integration, reduce power consumption, size, and cost.
4. Modularity and plug-and-play standards for communications and power must be in place for ease of sensor integration, substitution, and platform compatibility. Ethernet 10/100/1000 Base T, and TCP/IP and FTP protocols, are considered standard today and should be used consistently within observatories.
5. Take advantage of enhanced computing power of embedded Digital Signal Processors (DSP) and Field Programmable Gate Arrays (FPGA) for signal processing to maximize signal to noise ratio and minimize signal bandwidth for telemetry, the so-called "smart sensor."



Deployment of the Autonomous Vertically Profiling Plankton Observatory (AVPPO) at the Martha's Vineyard Observatory. The AVPPO is an underwater winch and buoyant sensor platform containing bio-optical (irradiance, ac-9, OBS), physical (turbulence, ADCP), chemical (O_2, nitrate) and biological (Video Plankton Recorder, fluorometer) sensors. Profiles are made to the air-water interface once per hour while data are telemetered to shore in real-time. For more information, go to http://4dgeo.whoi.edu/vpr.

6. Simplify and accelerate transitioning of research tools into operational oceanography. Enhanced funding opportunities are necessary to allow more-rapid transition of sensors from prototype to the user community. Encourage small business investment in sensor development.
7. Although viewed as being unglamorous, research on biofouling is essential if long-term instrument deployments will be successful. Fouling occurs at multiple scales and from multiple sources. Biological growth (bacterial film to invertebrate settlement) can be inhibited using toxic substances, appropriate surface characteristics, and UV light. Biological and electrochemical corrosion can be slowed by attention to materials, surface coatings, and removal of stray electrical current.
8. Funding needs to be made available for engineers to consider MEMS, microfluidics, and other approaches to miniaturization and, ultimately, cost reduction for individual and integrated sensor systems.
9. Funding agencies should enhance their programs in ocean sensor engineering with the objective of quickly bringing ideas to commercialization. This includes extending the duration of projects so that instruments may be developed and fully tested within a single project.
10. The research community needs to establish centers that would: act as a clearing house for information on sensor development; provide standardization of communications, power, and physical connections, and facilities for calibration, maintenance and training in use of specific sensors/instruments through community-wide workshops; evaluate sensors/instruments for sufficient robustness for operation in remote, harsh environments (e.g., deep-sea, high latitudes, etc); certify instruments; and provide the infrastructure for educating the next generation of engineers and technologists in sensor design and operation (micro mechanics, electronics, fluidics, physics, chemistry, acoustics, optics, and sea-going technologies).

Box 13. Cyberinfrastructure: The Glue of the Observatory

Contributed by Larry Smarr, Jacobs School of Engineering, UCSD, and John Orcutt, Scripps Institution of Oceanography

ORION will transform the way ocean science research is conducted by providing all oceanographers with access to the sea at any time. ORION's integrated global network of real-time, open observatories and instruments will deliver data and data products to the oceanographic community through a modern grid-based computing, visualization, and data system. This modern computing system will require state-of-the-art cyberinfrastructure (CI). Given this need, a CI Working Group at the ORION workshop reviewed and endorsed the goals of the Ocean.US Data Management and Communications (DMAC) Report (available at http://dmac.ocean.us/dacsc/imp_plan.jsp) as a good beginning for ORION. The vision for DMAC includes interoperability; open, easy access; reliable, sustained, efficient operations; effective feedback; an open design and standards process; and the preservation of data-products. ORION should build on the DMAC's progress; however, many challenges remain.

Although DMAC provides a good basis for CI, there are several advanced requirements for ORION. Security is an issue: Instruments can be resolved because IP addresses and bidirectional communications are the norm (instrument control, firmware, and software modernization; interactivity with the environment). Security methods must be well developed to prevent unintended modifications to ORION instrumentation. In addition, the data access system must be able to inherently control access to individual scientist experiments (e.g., instrument development). Persistent archives should be maintained by the system, including a metadata chain to track data changes. The system must provide access to data in near real time with latencies of, at most, a few seconds. Quality control (QC) and metadata descriptions must be available at some level to permit immediate use, while QC metadata ornamentation will be a continuing, tiered process. The data access model is likely to be federated in a data grid and computing capability should be available through a computation grid. While large clusters and parallel machines will be used for specific computations around the world, extremely high-speed access to both data and computation is critical.

The CI for ORION will require data management, communications, and data and information transport; networking, including a monitoring/management and event detection/notification system; adaptive control systems; data discovery mechanisms and metadata browsers (e.g., Google); library of data manipulation tools (e.g., sub-setting, re-gridding); visualization, including a library of advanced analysis/visualization tools; and computing, including a library of community modeling and data assimilation software. Routine now-casting and archiving of analyzed fields should be available as well as on-demand forecasting capability to support special field experiments. ORION's long-term viability depends upon the observing systems and the success of CI, and the continuing transition of systems through research, development, and operations. Cross training of scientists, engineers, and technicians will be critical to this effort. Domain scientists (oceanographers in this case) have a tendency to look upon computer scientists as code monkeys; the resulting effect upon cross-disciplinary research and applications is predictable. This culture must be changed at all costs.

Data Policy. ORION's default data policy is that the system is open and instruments are localized as IP addresses on a sensor web. The CI for the system should be well enough thought out that there is no need for back-channel access by scientists, engineers, or technicians. Although a web portal is important, the system must provide application programming interfaces (API) for a variety of software.

Metadata. A major task, which should be conducted in collaboration with the Integrated Ocean Observing System (IOOS), is the development of and community participation in metadata and data model standardization efforts to ensure that community standards support ORION needs. A data ontology for ocean sciences must be developed to allow data discovery and subsequent data access.

inside and outside oceanography. The Ocean.US Data Management and Communications (DMAC) Report (Hankin et al., 2004) provides a useful starting point for ORION. Developing common ground and an agreed on framework so that disparate efforts are cumulative rather than competitive is a high priority. Important lessons regarding strategies for development can clearly be gained from other large science endeavors, notably the development of cyberinfrastructure to support the large astronomical telescopes and the contemporary National Virtual Observatory initiative. We need to understand these lessons and use relevant elements to shape our plans. ORION is ideally placed to manage the community discussion to develop a framework for developing an oceanographic cyberinfrastructure, and then to coordinate with other communities on common needs. The science that ORION will enable should fundamentally change our understanding of our planet; the technology created to build ORION may have equally important impacts. A successful ORION cyberinfrastructure will have the following characteristics:

> Connecting an instrument to the infrastructure, and capturing the instrument data and metadata in ORION archives should be a straightforward, reliable process. Protocols and standards should exist to ensure that instruments are interoperable on different observatory networks. Implementations should ensure that the integrity of associations among data, metadata, and physical devices are preserved and the opportunity for human error minimized. Authorized users should be able to command and interrogate an instrument through straightforward interfaces. Although a web will satisfy many end users, the system must also provide a collection of well documented application programming interfaces (API) with open source, documented, and functional reference models for a variety of software development environments as well as a well engineered web services interface.

> Preservation of raw and derived data products, and ensuring their accessibility, will be a primary function of ORION. In many respects, the primary product is data. Persistent archives should be maintained by the system including a metadata chain to track data changes over time. Quality control and assessment and rich metadata descriptions of the data must be widely available globally to permit immediate use, while quality assessment annotations will be a continuing process. Data should be easily located and accessed. Although the system must support the varied and distributed forms of marine data and metadata, users should be unencumbered by traditional barriers such as data formats, volumes, and distributed locations. Heterogeneity of instruments, software, and data will be a fact of life and a source of scientific insight. A key objective will be to ensure that this heterogeneity provides opportunity rather than complexity for observatory users and operators.

Data discovery tools should integrate cooperating systems to make data discovery seamless across disparate data archives. Data discovery refers to the ability of the user to "find" specific data at specific locations without knowing a priori whether the data exist or where the data may be stored. For the astronomers, existence of archives with well-described metadata catalogues has led to the development of powerful tools for searching, visualizing and accessing data sets. That, in turn, has increased the scientific usefulness of that data. For example, the Hubble Space Telescope archive has delivered three times the data to archive users as it has to PIs.

Users should be able to access computational resources for manipulating data and carrying our modeling and simulations activities on demand. For example, assimilative ocean models continue to mature, and are increasingly being incorporated into oceanographic field programs, yet are extremely computationally intensive. Although large clusters and parallel machines will be used for specific computations around the world, extremely high-speed access to both data and computation is critical. Computing capability should be available through a computation grid. A federated data model allows the community to foster domain-specific centers of expertise where methods of automatic quality assessment can be improved and quick feedback about problems can be generated.

Distributed collaborations should be enabled by tools that support the exchange of complex information and make decision-making possible in real time. It is unrealistic to expect all relevant science parties to be collocated. Thus, ways to facilitate interactions among researchers during an experiment is a priority.

Security methods must be well developed to prevent unauthorized modifications to the ORION instrumentation or archives. The system must be able to inherently control access to individual scientist experiments, for example, instrument development. The use of the Internet by financial institutions to support customers provides encouragement that these problems are not insurmountable.

The default data policy for ORION is that the system is open. The ability to detect and respond to episodic events and to run real-time assimilative models depends on immediate data availability.

Automation of control functions will be a necessity for ORION. Observatories will operate 24 hours a day, 7 days a week over many years or even decades. A large number of scientific observations and experiments will coexist at any given time, with the possibility that an interesting event (e.g., an eruption at a spreading center) might change operational priorities on a moments notice. The desire to detect and respond to episodic ocean processes is a fundamental oceanographic need. The challenge will be to optimize the use of the resources of the facility, and minimize the interference between various observatory operations, to maximize the science achieved. The diversity and number of deployed systems will render a purely reactive control model of the observatory inefficient and slow. Consequently tools for capturing science objectives and relating these to resource management, so called scheduling and replanning tools, will be important elements of ocean observatory systems.

The investments in cyberinfrastructure will come from a variety of sources, and be distributed to a large number of performers. How can we ensure the individual elements result in a functional system? Or put another way, how can we ensure that the opportunity to contribute to the cyberinfrastructure is open to all? An open design process and standards based implementation is essential. Standards and protocol definitions must be published openly and the standards development process open and inclusive. Fostering buy-in from all stakeholders is an essential element of the process. The resulting design and standards must be of sufficient breadth and quality to guarantee interoperability of all observations and products. The initial capital investment should be incremental to take advantage of outside developments (e.g., hardware and software, concepts). Invest only when needed, so can use latest best.

There are established synergies between the cyber-infrastructure needs of scientists and the research interests of computer scientists. The need for distant collaboration led the high-energy physics community to create the World Wide Web (see http://www.w3.org/People/Berners-Lee/ShortHistory.html). Mosaic, the first graphics-capable browser was created by National Center for Supercomputing Applications, an organization whose charter is to create computing and information technologies to enable scientific discovery. CERN, the world's largest particle physics center, lists creation of the World Wide Web as one of their three greatest achievements (see http://public.web.cern.ch/Public/Content/Chapters/AboutCERN/Achievements/WorldWideWeb/WWW-en.html). The cyberinfrastructure needs of the ocean community provide fertile research opportunities for computer scientists. Consequently, building strong collegial ties and collaborative efforts with the computer science community provide a means to greatly increase ORION capabilities.

Engineering and Technology Working Group

- Kenichi Asakawa, Japan Marine Science and Technology Center
- Arthur Baggeroer, Massachusetts Institute of Technology
- Jim Bellingham, Monterey Bay Aquarium Research Institute
- Jon Berger, Scripps Institution of Oceanography
- Kandace Binkley, National Science Foundation
- Albert Bradley, Woods Hole Oceanographic Institution
- Richard Camilli, Woods Hole Oceanographic Institution
- Alan Chave, Woods Hole Oceanographic Institution

- Dale Chayes, Lamont-Doherty Earth Observatory
- Dennis Conlon, National Science Foundation
- Daniel Davis, Monterey Bay Aquarium Research Institute
- Mike DeLuca, Rutgers University
- Duane Edgington, Monterey Bay Aquarium Research Institute
- Lee Freitag, Woods Hole Oceanographic Institution
- Sherryl Gilbert, University of South Florida
- John Hamilton, Monterey Bay Aquarium Research Institute
- Phil Hart, Global Marine Systems Limited
- Bruce Howe, University of Washington
- Bill Kirkwood, Monterey Bay Aquarium Research Institute
- David Maier, OGI School of Science and Engineering
- David Martin, University of Washington
- Gene Massion, Monterey Bay Aquarium Research Institute
- Bob McClure, Biosonics, Inc.
- Christopher McPherson, Ocean Design, Inc.
- Kyohiko Mitzusawa, JAMSTEC
- Greg Moeller, Bluefin Robotics Corporation
- David Murphy, Sea-Bird Electronics, Inc.
- Robert Newman, Scripps Institution of Oceanography
- Peter Phibbs, Mallin Consultants Ltd.
- Frank Rack, Joint Oceanographic Institutions
- Keith Raybould, Monterey Bay Aquarium Research Institute
- Konstanze Reichert, OceanWaveS
- Henrik Schmidt, Massachusetts Institute of Technology
- Nazeeh Shaheen, NAUTRONIX MariPro INC
- Mark Sibenac, Monterey Bay Aquarium Research Institute
- Hanumant Singh, Woods Hole Oceanographic Institution
- Larry Smarr, University of California, San Diego
- Frank Vernon, Scripps Institution of Oceanography
- Dana Yoerger, Woods Hole Oceanographic Institution

V. Education

Blanche Meeson (Moderator/Rapporteur)

Ocean-observing systems provide an opportunity to transform the way we experience and work in the oceans. Ocean-observatory research and engineering will include exploration, discovery, and innovation at its most captivating, in one of the most challenging environments to study. The allure of the unknown oceans and the technologies to be deployed in ocean observatories will capture the imagination, and inspire and motivate youth and adults to embark on careers allied with the oceans.

Our nation is faced with major challenges in the supply of new scientists and engineers into the labor force, and in the public's understanding of Earth's life-support system and the oceans' role in it. Our economy is increasingly dependent on science and technology innovations; yet fewer and fewer youth are pursuing course work that will prepare them to be successful in these careers. Indeed, ORION science and technology itself, to be successful, depends not only on today's workforce, but on tomorrow's. Today's workforce will be

The U.S. education system is very large, complex, and driven by different challenges in every community. Many American children and adults lack basic scientific literacy and are uninformed about the importance of the Earth and the ocean systems in their lives. At the same time, our economy has become more dependent upon science and technology innovation, and public understanding of ocean and coastal science and technology issues has become more important, as an increasing number of Americans live within 10 miles of the coast.

- 47 million public school students; 38.8 million K-8th graders, 39% are historical minority populations (National Center for Education Statistics, http://nces.ed.gov/edstats/)
- 1.8 million elementary teachers; science, math, and technology education proficiency for elementary educators lacks common benchmarks (Hart-Rudman Commission, 2001)
- 3,700 schools of higher education prepare tomorrow's workforce (e.g., educators, scientists, technologists, policy-makers) (National Science Board, 2004)
- Latest test scores show that U.S. high school seniors place at or below the international average (National Science Board, 2004)
- 60% of the public lack basic knowledge about the oceans (e.g., more life in the oceans than on land, most of the oxygen we breathe comes from the sea) (The Ocean Project, 1999).
- Minority population is expected to be majority population by 2012 for new entrants into the workforce; minority populations historically have not participated in science and technology careers; underrepresented minorities were more than 40% of the population in 2000 yet received only 13% of the science and engineering bachelors degrees. (National Science Board, 2004; http://www.nsf.gov/sbe/srs/wmpd/sex.htm
- Females have achieved parity with the population for overall degrees received in science and engineering. However, in engineering and the physical and computer sciences, females continue to lag far behind with only 20-42% of the degrees awarded in 2001. (National Science Board, 2004; http://www.nsf.gov/sbe/srs/wmpd/sex.htm; http://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2000601

called upon to build the first observatories and create their cyberinfrastructure, to operate the instrument and computer systems, and to maintain them. Will the workforce be able to keep pace as the demand for technical help grows? The future professionals—scientists, engineers, cyber-technologists, technicians, operations staff and educators—are already in elementary and middle school. We now know, to reverse the current downward trend in students opting for science careers, many more students, especially those from underserved and under-represented groups, must be inspired, motivated, challenged, and nurtured in the sciences.

To accomplish the goals of (1) increasing participation in science and technology careers, in particular, in ocean sciences and (2) increasing awareness, understanding, and appreciation of the oceans' role in the Earth system, we need an environment that values science and technology careers; a society that values and rewards those who educate, nurture, and train our youth to successfully pursue those careers; and a society with a vital ocean science and technology enterprise that employs scientists, engineers, technicians, operations professionals, and educators.

The connection between the unknown and the known in the oceans will be used by educators to advance science and technology learning among all students and adults. ORION science is especially 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 (NSES) (Table 2). As educators and students develop understandings of the oceans' physical, biological, chemical, and geological processes and their inter-relationships, they develop understandings key to these disciplines and also practice reasoning skills that assimilate multidisciplinary data products into their world view.

Table 2. National Science Education Standards' Categories
Unifying concepts and processes in science • Systems order and organizations • Evidence, models, and explanation • Change, constancy, and measurement • Evolution and equilibrium • Form and function
Science as inquiry • Understanding of scientific concepts • An appreciation of "how we know" what we know in science • Understanding of the nature of science • Skills necessary to become independent inquirers about the natural world • The disposition to use the skills, abilities, and attitudes associated with science.
Science and technology • Identify and state a problem • Design a solution including a cost and risk-and-benefit analysis • Implement a solution • Evaluate the solution
Physical science
Life science
Earth and space science
Science in personal and social perspectives
History and nature of science

Educators will be able to use ORION education products to help people become informed and develop a life-long interest in the oceans' role in the Earth system. ORION scientists will be able to tell compelling stories that will enable the public to see the oceans in new and more meaningful ways. ORION will use participatory and hands-on efforts such as citizen science and technology projects; near-real-time digital simulations; and audio, video, and museums and aquaria exhibits to engage the public in their scientific quest.

Scientists and educators attending the ORION workshop made six major recommendations to address ocean/Earth system education within ORION (Table 3). These recommendations address the infrastructure required for a coordinated and coherent education program, and the national needs in science and technology education where ORION can make a unique contribution.

1. Create an Education and Communications Coordination Office

The primary purpose of the Education and Communications Coordination Office is to ensure that the ORION education and communications efforts are sufficiently coordinated, coherent, and sustained so the education and communication goals of the ORION program can be achieved. The office would act as a focal point for ORION education and communications at the national level. To fulfill this purpose, the office will work with the ORION PI's, OOI sites, and ocean-science educators to

a. identify, support, and guide implementation of education and communications efforts throughout the ORION
b. Support an ORION education network with regional facilities (e.g., Centers for Ocean Science Education Excellence [COSEEs])
c. develop common messages and themes that are shared and used by all education and communication efforts
d. provide education and communication efforts that
    i. support the ORION research and technology community by providing services that prepare them to address the "category 2" requirements for ORION science proposals such as a scientist's resource guide to education efforts and collaborations that address ORION education priorities and goal
    ii. inform and engage stakeholders by developing a public-awareness strategy with coordinated campaigns that target specific audiences (e.g., 90-second radio programs and video segments on existing programming)

Table 3. Specific Goal
ORION will use ocean-observing science and technology infrastructure to engage communities in ocean exploration and discovery; increase awareness, understanding, and appreciation of the oceans; strengthen science and technology education; and inspire, motivate, and nurture people from all backgrounds to pursue science and technology careers generally, and ocean sciences careers specifically.
Contribute to a national ocean observing education infrastructure by creating 1. An ORION education and communications coordination office 2. A data management and content translation facility 3. A community of educator leaders who coordinate, sustain, and support local education leadership in their science education improvement initiatives[1]
Address key national education needs for which ORION is uniquely suited 4. Engage communities across America in ocean-observatory science and technology to develop their understanding and appreciation of the vital role the ocean plays in the Earth system and in their lives 5. Promote the development and diversity of the ocean-related workforce 6. Create an education incubator facility whose focus is to advance understanding of science and technology learning and practice in areas where ocean observatories can uniquely contribute
[1]Includes undergraduate education, k-12 educators networks and the local communities

iii. support educators, including the development of educator-leaders (see below)

e. enable the data management and data translation facility (see below) to routinely provide information translations* designed to serve researches, stakeholders, and educators
f. support development of ORION community engagement in state-based Alliances by providing services that help ORION educators and scientists and the local education leadership build partnerships that are mutually beneficial
g. coordinate with national ocean/Earth system science and technology education efforts so that ORION education efforts are instrumental in furthering the national education agenda in Earth and space system science.
h. encourage efforts that support performance evaluation and assessment of individual education efforts (programs, products, practices) and the ORION education/communications program as a whole

Implementation will be done primarily by ORION scientists, with insight and guidance provide by the coordinating office as needed.

The coordinating office should be organizationally incorporated into the ORION program office, but physically distributed. One function of the central coordinating office would be to raise non-federal funds to augment the federally funded ORION education and communications program.

2. Create a data management and content translation facility

The data management and content translation facility will transform ORION research results, technology innovations, and data into ready-to-use forms for a variety of education and communication audiences. These translations would include real-time, near-real-time, and event-driven data and visualizations accompanied by engaging content that can be used in the wide range of venues, including, classrooms, science center exhibits, Internet sites, television, and community programs designed for children and adults.

The facility will provide a systematic process for information translation based on the successful model used by NASA for communication professionals. For ORION it would be adapted and extended for education professionals and students, and would incorporate related models developed by learning center and park professionals for their environments. Initially, information liaisons will act as bridges between the information translators and the diverse education professionals who wish to use the translated resources. Liaisons will identify needs and processes that are common across education professions, and those that are unique to individual professions. These commonalities and differences will drive improvements in the translation and story-development capability. It is likely that this capability will be a joint ORION and IOOS capability since the IOOS education community has recommended the formation of a similar capability.

This facility will also provide an effective process for education professionals to identify and acquire the materials that are the products of this translation process. A clearinghouse (data mining web site) for sharing the translations (stories, visualizations, and data) and subsequent learning materials and education tools that use these translations has been recommended along with background materials for educators and education product developers. The Digital Library for Earth Systems Education (DLESE), an education community resource that provides a clearinghouse for educational resources and a variety of educational services, has committed to being a partner for these efforts and to help provide access to community data, tools, and learning products.

Because of the importance of graphic manipulations of data, analysis, and modeling to developing deeper conceptual understandings in mathematics and science, and the recognition that most people are visual learners, ready access to ORION data and visualizations, in useful forms, are of special interest to educators. Participation of educators early in the planning and development of data protocols for ORION can help ensure that the information products meet educators needs. In particular, these products should serve as a resource for recognizing patterns and for making quantitative tests of students' hypotheses.

The strength of a data management and content translation capability is three fold. First, a trusted provider status develops between the translation facility, and the education and communication professionals who use it. Consequently, these professionals rely on the translation facility as a source of new content. Thus, ORION materials and the associated messages and themes are promulgated on a much larger scale than ORION could accomplish directly. Second, a low-cost, low-effort mechanism exists for ready re-use and re-purposing of translated materials for a new (unplanned) purpose. Third, the facility makes possible a planned launch strategy that ensures the message and theme, and resulting programs and products, reach the audiences at the most effective and efficient time and at the appropriate level of detail.

3. Develop a community of educator leaders who coordinate, sustain, and support local education leadership in their science education improvement initiatives

A community of educators who use ORION information and who are leaders in their local education communities will be created through the formation of a collaborative education network coordinated by the ORION Education and Communications Coordination Office. The ORION education network will focus on building and continuously developing a community of science, technology, engineering, mathematics (STEM), and geography educator-leaders with expertise in ocean sciences content, concepts, and technologies; ocean sciences quantitative skills; observatory science and technology; and appropriate pedagogical content. These education leaders will serve as expert resources for the broader collaborative Earth/geography/space system education network, helping to build capacity to use ORION information products, and to create and use ORION-related learning resources. These leaders will be resources for professional development of educators in their disciplines and local communities, and will act as catalysts for infusion of ocean and Earth system science into their discipline, local community, and state education improvement initiatives at all levels.

Initial efforts will focus on establishing this community from existing ocean education networks such as NSF's COSEEs, the American Meteorological Society's DataStreme Oceans, the American Meteorological Society's Maury network, NOAA Sea Grant network, National Marine Educators Association, JASON educators, REVEL educators, NOSB educators, GLOBE educators/partners, and many others. Follow-on efforts will extend the reach of the network by embracing regional and state-based Earth/space science and geography educator networks.

The importance of tapping existing networks and programs and their participation in the larger Earth/geography/space system collaborative cannot be overstated. Because the education system in the United States is large, complex, and driven by local issues, and 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 they act alone. In addition, as part of a large collaborative network, local efforts can be coordinated across the network to provide continuity and coherency of purpose. Highly effective local education practices and exemplary systemic, broad-based improvements from one local area are more likely to be propagated throughout the network, thereby, improving the likelihood that common education goals will be achieved.

4. Engage communities across the United States in ORION science and technology to develop their understanding and appreciation of the vital role the ocean plays in the Earth system and in their lives

Most Americans know little about the oceans and how their lives are tied to the oceans. To develop a populace that is knowledgeable about the oceans is a major endeavor that must be sustained over a lifetime. It will require a coordinated effort by multiple groups working together, including the ORION education network.

Informal, self-directed learning is the way most American adults acquire new knowledge. Having a community of ORION educator-leaders with expertise in informal education is an effective mechanism to foster and sustain lifelong learning of the oceans. They will support learning in a wide range of venues and situations with effective learning opportunities for all types of learners (e.g., visual, auditory, kinesthetic). Because progress in science and technology is so rapid, science and technology learning opportunities must be many and varied; learning must not be restricted to school-house years.

Life-long learning activities engage people of all ages in participatory ocean science and technology learning and in public programs. Participatory efforts such as citizen science or technology projects are possible for all ages. Science projects engage adults or youth as amateur or lay scientists in the collection or analysis of data in much the same way that amateur astronomers have assisted in the identification of comets or other celestial bodies. Other activities might involve school groups, youth groups, or entire communities. Each group would participate in an ORION research project by providing a capability that is needed for the overall research objectives (e.g., monitoring the operation or track of a buoy, glider array, AUV, or tagged animal). In turn, the local educator-leader would help develop the group's understanding of ocean processes and the contribution of their project to ocean sciences. Efforts like this could be extended by developing sister schools, groups, or communities.

Technology projects could engage adults or youth in team design-build competitions much like the Marine Advanced Technology Education (MATE) Center's ROV competition (see www.marinetech.org/rov_competition/index.php for more information), or design-build competitions where whole communities work together and then compete with other communities to deploy their device for some period on an observatory to fulfill a specific student science objective.

Other projects might include student or amateur experiments designed to be carried out on the observatory using equipment on the facility specifically set aside for their use. Such programs could address the standards for technology literacy and the science and technology content standards of the NSES. A highly visible award structure would be part of the activity.

Summer camps and youth experiences could also be crafted that would provide students with immersion experiences in much the same way that summer foreign language immersion or sports camps do.

Use of ORION assets in less participatory modes of engagement can also inspire, motivate, and develop ocean stewards with a deep and enduring appreciation of the role the ocean plays in the Earth system and in our lives. Concepts include permanent and traveling exhibits for museums, science centers, and aquaria. Exhibits would have both authentic artifacts such as gliders, ROVs, AUVs, buoys, and hands-on activities. Another concept might be a "traveling trunk"—a small-scale, hands-on set of models, activities, games, and stories that could easily be shipped from learning center to learning center. The traveling trunk would be appropriate for the large number of small science learning centers around the country or could be purchased by libraries for their loan programs, or by child care and community groups for their after-school programs.

Multiple media outlets will be used to introduce most Americans to ORION, including television, Internet web sites, print and radio. The diversification of outlets has created more opportunities for science and technology from programs like ORION to reach the public. It also means that programs like ORION must be more savvy about how to prepare and package their stories so that these outlets not only know about the ORION stories, but also trust the quality of the product sufficiently to seek out ORION content when planning and producing programs.

5. Promote the development and diversity of the ocean-related workforce

ORION can contribute significantly to the development of ocean educator-leaders who are key to increasing the size and diversity of the ocean science workforce. Participation in ORION internships, mentoring relationships, and educator-at-sea experiences are mechanisms to deepen educator-leaders' understandings and skills, and develop new educator-leaders. Educator-leaders inspired by ORION professionals and participatory programs pass that inspiration along to their colleagues and students for many years. As these educator-leaders deepen their knowledge and understanding of science, mathematics, technology, and inquiry concepts, they are better prepared to assist in the professional development of their colleagues, and the development of their students.

An effort such as an Ocean GLOBE would integrate scientific concepts and mathematics for students, develop educator-leaders, and make use of data translations in educational settings. This effort would use ORION data, and link with students, teachers, and the public through modern, inquiry-based science and technology learning. Educator-leader development would include participation in state alliances and scientist-educator partnerships. Educator-leader development, with expertise in Ocean GLOBE would be targeted to those districts and states where GLOBE has been adopted as a curriculum component by the local education leadership. In this way the Ocean GLOBE educator-leaders will help the entire ocean educator-leader community develop relations with their local education leadership and identify areas where they can further local education improvement efforts.

Programs like ORION have a unique ability to address critical system deficiencies in educating and motivating under-represented groups in science, mathematics, and technology. Many of the programs mentioned (internships, mentoring, at-sea programs) for educators are also important for students, especially those who are underserved and under-represented and who have few role models in their communities. By making available career information that is specific to underserved and under-represented groups, these students can be motivated to perform successfully in their course work. ORION education partners can provide the needed information in many forms (written, oral, testimonials) and make that information available at multiple points along an individual's education path from early learning to adult learners.

Just as career materials will be needed to introduce, motivate, and inspire youth from underserved and under-represented populations to pursue ocean sciences and engineering careers, so will special programs and learning materials be needed in classrooms, at after-school and youth programs, and at other informal learning venues. ORION can contribute to improvement in these areas by partnering with programs and organizations that have a record of success at increasing the performance and the participation of these groups in science and technology. Contributions from ORION could be developing content for programs and learning materials, providing scientists and technologists as mentors for students and educator-leaders, and providing opportunities for educator-leaders who focus on sustained development of educators, adults, and youth in these populations.

ORION programs should also address the traditional inequalities in the ocean sciences workforce. They should capture and retain the interest of girls as they traverse the difficult teenage years where most girls perform poorly in the required gatekeeper courses.

6. Create an education incubator facility whose focus is to advance understanding of science and technology learning and teach in areas where ORION can uniquely contribute

Information literacy—the ability to handle, analyze, and interpret data—is expected to be one of the key skills needed to be successful in the 21st century. Yet, there are large gaps in our knowledge of learning and instruction associated with the use of data and technology, scientific inquiry, learning of unifying and interdisciplinary concepts, and how to develop skills and abilities associated with mathematical modeling. We also know little about how to develop this literacy in individuals with different learning styles (e.g., visual, auditory, kinesthetic) and disabilities.

Learning about the oceans requires integration of foundation science concepts from several different disciplines through the use of mathematics, modeling, and data. The sustained and diverse measurements gathered by ORION provide unlimited opportunities to examine unifying science concepts and develop the inquiry skills of educators, students, and the public. ORION is also an ideal model for understanding how people learn science, and transforming that knowledge into best practices for educators.

The education incubator facility directly linked with ORION would conduct research into how people learn science, and then translate those research results into innovative educational practices (techniques, strategies, and approach) that are highly effective for science learning by students, adults, and educators in a wide range of settings (K-12 and undergraduate instruction, informal environments) and from a wide range of backgrounds. This is the first time a geoscience education research center would be directly associated with a major scientific research endeavor and thus would serve as a model for how education research can go hand-in-hand with scientific research.

Education Working Group

- Rick Baker, Ocean Institute
- James Brey, University of Wisconsin Fox Valley
- Vicki Clark, Virginia Sea Grant/VIMS
- Steven Conway, Texas A&M University at Galveston
- Susan Cook, National Science Foundation
- Margaret Davidson, NOAA Coastal Services Center
- Annette deCharon, Bigelow Laboratory for Ocean Sciences
- Sharon Franks, Scripps Institution of Oceanography
- Edward Geary, Colorado State University
- Henny Groschel, University of Miami
- Michelle Hailey, Girl Scouts of America Research Institute
- Peggy Hamner, University of California, Los Angeles
- Amy Holt-Cline, University of New Hampshire
- Tracy Kirby, Ocean Institute
- Barbara Kirkpatrick, Mote Marine Laboratory
- George Matsumoto, Monterey Bay Aquarium Research Institute
- Janice McDonnell, Rutgers University
- Carrie McDougall, NOAA
- Maia McGuire, University of Florida Sea Grant
- Blanche Meeson, Ocean.US
- Laura Murray, University of Maryland-Center for Environmental Sciences
- Margaret Olsen, Southeast Center for Ocean Sciences Education Excellence
- Nancy Penrose, University of Washington
- Lisa Pitman, University of Miami
- Morgan Richie, Ocean Institute
- Veronique Robigou, University of Washington
- Sarah Ross, NOAA
- Leslie Sautter, College of Charleston
- Judy Schoenberg, Girl Scouts of America Research Institute
- Rochelle Slutskin, Anne Arundel County Public Schools
- David Smith, United States Naval Academy
- David Snyder, Gallaudet University
- Barbara Spector, University of South Florida
- Lundie Spence, SC Sea Grant Consortium
- Mike Spranger, University of Florida
- Jack Thigpen, North Carolina Sea Grant
- Carrie Thomas, North Carolina State University
- Jennifer Trask, Monterey Bay Aquarium Research Institute
- Sara Tweedie, Tweedie & Associates

VI. International Framework for ORION

For scientific, logistical, and economic reasons, the establishment of observatory networks will involve the combined efforts of a number of countries, and efforts need to be made early on to cooperate and coordinate with other nations. Although coastal and regional observatory networks will largely be set up and operated within a single country, some coordination among countries will be desirable depending on processes being studied, and on the proposed location of instrument arrays. For example, the proposed regional cabled observatory in the Northeast Pacific will be located in both U.S. and Canadian waters (see figure, opposite page). An international consortium of institutions including the University of Washington, the University of Victoria (Canada), Woods Hole Oceanographic Institution, the Jet Propulsion Laboratory, and the Monterey Bay Aquarium Research Institute have been planning this proposed project. In Fall 2003, full Canadian funding of $62.4 million for NEPTUNE Canada (NC, www.neptunecanada.ca) was announced. Funding came from the Canada Foundation for Innovation ($31.9M) and the British Columbia Knowledge Development Fund ($30.5M) and was awarded to the University of Victoria (UVic), which leads a consortium of 12 Canadian universities from coast to coast. This award can enable economies of scale, timing, and collaboration that would not otherwise be possible.

ORION's global component will involve even greater international coordination and cooperation in order to share resources and assets; to take advantage of mutual planning efforts and opportunities; and to avoid duplication or conflict of efforts. Although the focus of the ORION Workshop was on U.S. efforts, international links that already exist and those that could be established were discussed. Information papers were solicited describing international programs, such as GLOBEC, ICES and PICES, IMBER, ION, IODP, MOMAR (available at www.orionprogram.org under the link to the San Juan Workshop), and during the workshop, four presentations were made about international programs: Chris Barnes discussed the NEPTUNE Canada effort, Hitoshi Mikada outlined Japanese observatory efforts (e.g., see p. 124, box on ARENA), Roland Person presented a summary of European observatory developments (e.g., see p. 123, box on ESONET), and Steven Bohlen gave a presentation describing the IODP.

The importance of international cooperation and coordination was echoed in many of the working groups. The Biogeochemical Cycles Working Group identified the need for coordination, support, advocacy, and facilitation by existing international programs such as JGOFS, CLIVAR, GOOS, and POGO. The Earth Structure group identified international support as a key to success for installing geophysical observatories, citing ION, OSN, OceanSITES, and existing collaborations with Japan. It was noted that coordinating and partnering with international groups such as IODP, InterRidge, JAMSTEC, ESONET, and MOMAR to share costs and infrastructure will be needed for studies of plate dynamics and fluid-rock interactions and their influence on life. Topics of international scope were also identified, such as the global degradation of coral reefs (of interest to western Pacific as well as Caribbean nations) and impacts of dams on major rivers, such as in Asia and North America.

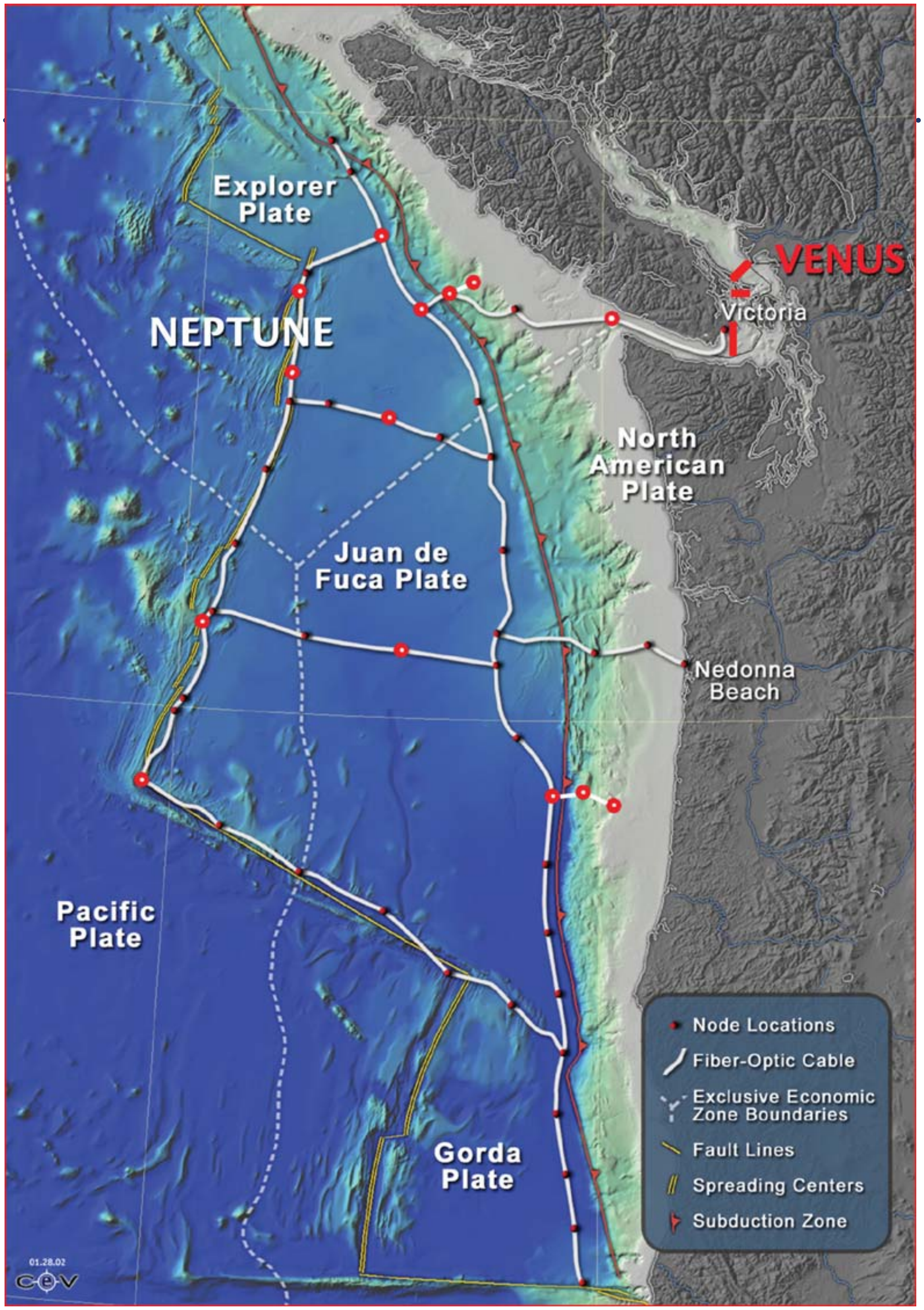


Figure VI-1. Proposed regional cabled observatory in the Northeast Pacific.

One particularly vital concern identified as requiring international cooperation and coordination was data management. The global science to be enabled by ORION will require access to data from the global network, part of which will be acquired by other countries. The ORION data management structure must be built in coordination with the international programs, in particular regarding:

- interoperability of ORION data management with other international systems.
- standardization of data and metadata formats both on syntactic and semantic aspects.
- harmonization of quality-control processes both in real time and delayed mode for some key parameters acquired by different networks and already used by a wide community of users.

A second concern is for the coordination of the resources needed to deploy and maintain the time series observatories, many of which are in remote regions and some of which are planned for sites with severe environments. International cooperation will be essential to ensure that the ship time, hardware, and human resources needed to sustain the global array can be found and that capacity building efforts lead to the development of many nations capable of operating elements of the array.

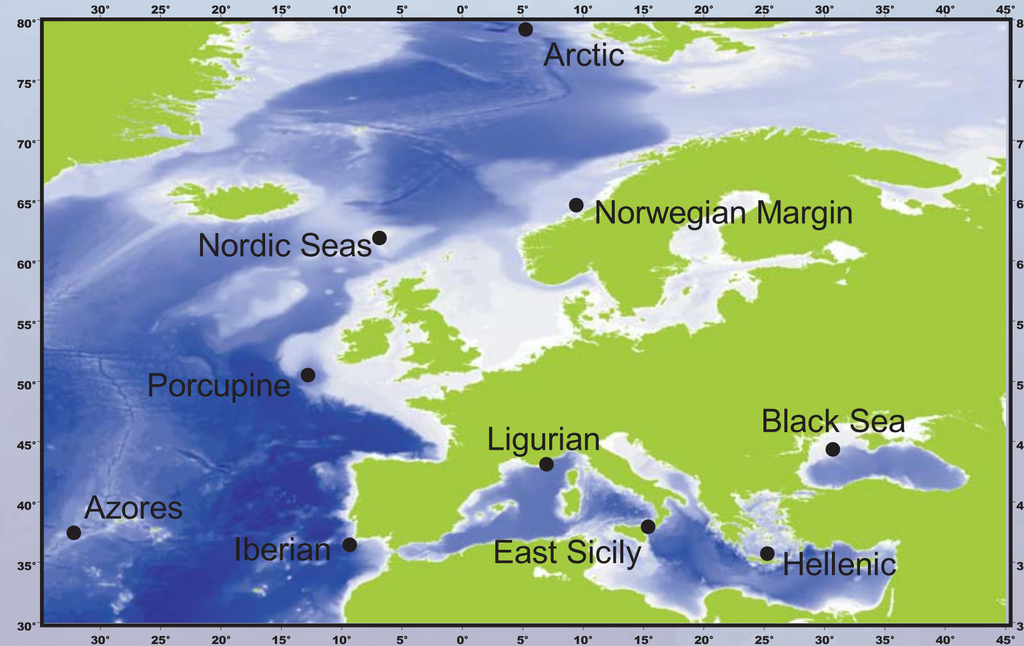
The community has already recognized the need for an international organization to coordinate and guide the implementation of a global time-series observatory network. In 2001, a multidisciplinary international Science and Steering Team was formed that includes 18 members from 11 countries and covers all disciplines of marine science (see p. 125, box on OceanSITES). A key task for ORION will be to ensure communication, cooperation, and coordination with this team, across these disciplines, and also among the broad cross-section of existing national and international programs.

Box 14. European Seafloor Observatory Network

Contributed by Martin Solan and Monty Priede, University of Aberdeen, United Kingdom

The European program for Global Monitoring for Environment and Security (GMES) has identified a need for a subsea surveillance system. The goal of the European Commission-sponsored European Seafloor Observatory Network (ESONET) is to monitor the solid Earth beneath the sea, processes at the interface between the solid Earth and sea, and processes in the water column. ESONET monitors the submarine terrain around Europe from the continental shelves to the abyss, an area of approximately three million square kilometers. This is comparable in size to the total land mass of Europe and is increasingly important for resources, such as minerals, hydrocarbons and fisheries. Only a small fraction of this realm has been explored, and new features and animal communities (e.g., cold-water corals and mud volcanoes) are discovered every year. The biodiversity probably exceeds that of the European land mass. There are natural hazards such as submarine slides and earthquakes with associated tsunamis. Human impacts on this zone are poorly understood. A prerequisite for management, conservation, and protection from hazards of this zone is the establishment of a long-term monitoring capability. Through a coordinated approach, ESONET will provide data to users on time scales from instantaneous (real-time hazard warning) to long term (archiving of data for tracking of global change around Europe).

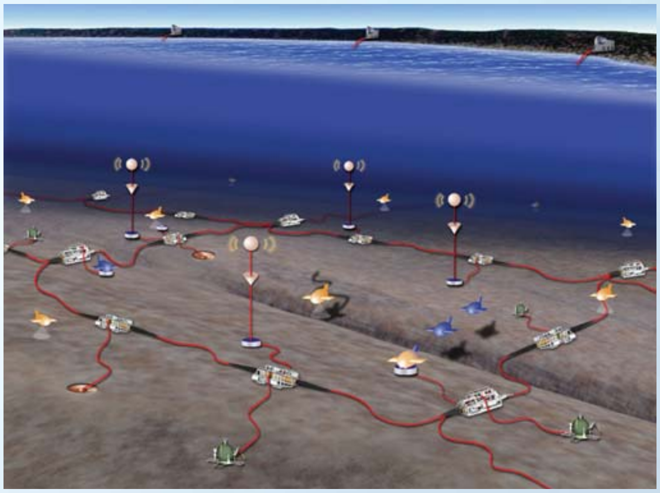
ESONET is proposed as a network of 10 regional observatories. These will provide representative sampling around Europe in contrasting oceanographic regions from the Arctic Ocean to the Black Sea (see figure). ESONET will be a federation of these regional observatories each with its own lead institution and implementation committee. ESONET will provide standardization, coordination, and data interchange. Many ocean sensors (e.g., optical imaging, chemical) have a limited field of detection so that a seafloor observatory can only sample a small fraction of submarine domain. To enhance the representative temporal and spatial sampling achieved from the array of fixed sites, a mobile response observatory is proposed for rapid deployment in areas of anthropogenic or natural disasters. This equipment will be flown from a centrally located environmental security center, arriving anywhere in Europe in fewer than 24 hours. Environmental managers and government agencies will thus have the critical and distinct advantage of access to geologic, hydrographic, biological, and chemical measurements as required.



Box 15. The Ocean ARENA Observatory

Contributed by Kenichi Asakawa, Japan Marine Science and Technology Center

In 2003, IEEE OES Japan Chapter organized a technical committee on scientific submarine cables, which proposed an ambitious scientific cable network called ARENA. Forty-five engineers and scientists with various backgrounds from private companies, universities, and research institutes participated on the committee, and carried out a technical feasibility study. ARENA has multidisciplinary objectives similar to those of ORION, and has a mesh-like cable topology as shown in the figure. Many types of sensors will be connected to the cable network with underwater mateable connectors, and will provide long-term, real-time, continuous, three-dimensional data via an IP network.



An artistic image of ARENA.

Because Japan is located near plate boundaries where catastrophic earthquakes occur periodically, seismic studies and disaster mitigation have the highest priority in ARENA. Thus, ARENA must be robust so that rare chances of monitoring large earthquakes are not missed due to cable faults caused by these earthquakes. This need is one of the reasons why ARENA adopted constant-current power-feeding system. Mesh-like topology is also important feature that will increase the robustness of the cable network.

JAMSTEC and some other participants have conducted studies on the power-feeding system and the optical-data transmission system. For the power-feeding system, a new current-to-current converter, which branches constant currents and is the key device for realizing a mesh-like cable network with constant-current power feeding, was proposed. Its basic functional capabilities were tested in experiments and by computer simulations. For the optical-data transmission system, a new method using Raman amplifiers as modulators of carrier light was proposed and tested. This method is compatible with the dense wavelength division multiplex system. The ARENA project will continue to evolve and will represent a useful partner with seafloor observatories planned by Canada, the United States, and Europe.

Envisioned future ARENA network.

Box 16. OceanSITES

Contributed by Uwe Send, Co-Chair, International Time Series Science Team, University of Kiel, Germany.

A multidisciplinary international Science and Steering Team was formed in 2001 at the request and with the support of CLIVAR (COOP), GOOS (OOPC), and POGO to begin developing the rationale and design of a global time-series observatory network, and to coordinate and guide its implementation. Currently, this team includes 18 members from 11 countries and covers all disciplines of marine science. It has developed a rationale for sustained global ocean time-series observations, and initiated an evolving pilot project that includes all existing and planned global sites that fulfill established criteria. A short version of a white paper for this project called OceanSITES is available (see www.OceanSITES.org). A number of sites in this global system already exist, for which the Science Team mainly acts to coordinate, integrate, and harmonize the operation and data management policy. Beyond that, the team is developing plans for the evolution and expansion of the system, by relying on and coordinating national plans and efforts. However, OceanSITES does not have a mechanism to fund any operations.

OceanSITES and its science team provide an international framework for major parts of the U.S. ORION effort. Through OceanSITES, links exist to relevant international programs such as CLIVAR, GOOS, SOLAS, IMBER, and the international carbon programs (through the IOCCP). At the same time, a strong interface between OceanSITES and ORION is guaranteed by the large representation of U.S. members active in ORION who are on the OceanSITES Science Team.

OceanSITES has already initiated an international data management effort for multidisciplinary time-series data that tries to build on existing international procedures, infrastructure, experience, and standards. The data management team was chosen to have representation from all ocean disciplines and assure coherence with other projects like WOCE, JGOFS, IMBER, CLIVAR, carbon, ARGO, and more. Thus, OceanSITES has the potential to provide the international standard for ocean time-series data formats and procedures. One requirement for elements/members in the OceanSITES project is an open data policy.

In the short term, it is unrealistic to envisage a completely distributed data network containing all necessary infrastructure (e.g., coherent quality control, guaranteed archiving). Therefore, OceanSITES has started implementing a distributed network that interconnects a small number of professional data centers. By the end of 2004, these centers will start archiving and distributing the first time-series data according to international standards. It is important that the ORION data system, which is being designed now, interface seamlessly with this international time-series data system, which will be operational in the near future.

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Appendix 1

Workshop Participants

Abbott	Mark	Oregon State University
Ammerman	Jim	Rutgers University
Armstrong	Roy	University of Puerto Rico
Asakawa	Kenichi	Japan Marine Science and Technology Cente
Atkinson	Larry	Ocean.US/Old Dominion
Austin	James	University of Texas at Austin
Badiey	Mohsen	University of Delaware
Baggeroer	Arthur	Massachusetts Institute of Technology
Baker	Rick	Ocean Institute
Bane	John	University of North Carolina
Baptista	Antonio	Oregon Health & Science University
Barnard	Andrew	WET Labs
Barnes	Chris	University of Victoria
Barth	Jack	Oregon State University
Batiza	Rodey	National Science Foundation
Beach	Reg	Consortium for Oceanographic Research and Education
Beardsley	Robert	Woods Hole Oceanographic Institution
Beauchamp	Patricia	Jet Propulsion Laboratory
Beaulieu	Stace	Woods Hole Oceanographic Institution
Bellingham	Jim	Monterey Bay Aquarium Research Institute
Bemis	Karen	Rutgers University
Berger	Jon	Scripps Institution of Oceanography
Bergmann	Trisha	University of Maine
Bigidare	Robert	University of Hawaii
Binkley	Kandace	National Science Foundation
Bissett	Paul	Florida Environmental Research Institute
Blaire	Jay	University of Miami
Bogden	Philip	Southeastern Universities Research Association
Bohlen	Steven	Joint Oceanographic Institutions
Bohnenstiehl	Del	Lamont-Doherty Earth Observatory
Boicourt	William	University of Maryland Center for Environment
Boss	Emmanuel	University of Maine

Boumeester	Bjorn	University of Puerto Rico, Mayaguez
Bradley	Albert	Woods Hole Oceanographic Institution
Brey	James	University of Wisconsin Fox Valley
Brink	Kenneth	Woods Hole Oceanographic Institution
Brown	Kevin	Scripps Institution of Oceanography
Bruno	Michael	Stevens Institute of Technology
Burgett	Mark	Ocean Design, Inc.
Camilli	Richard	Woods Hole Oceanographic Institution
Campbell	Janet	University of New Hampshire
Campbell	Lisa	Texas A&M University
Can	Ali	Woods Hole Oceanographic Institution
Cannat	Mathilde	Institute de Physique do Globe de Paris-CNR
Carbotte	Suzanne	Lamont-Doherty Earth Observatory
Chadwell	Dave	Scripps Institution of Oceanography
Chang	Grace	University of California, Santa Barbara
Chao	Yi	Jet Propulsion Laboratory
Chave	Alan	Woods Hole Oceanographic Institution
Chavez	Francisco	Monterey Bay Aquarium Research Institute
Chayes	Dale	Lamont-Doherty Earth Observatory
Clark	Larry	National Science Foundation
Clark	Vicki	Virginia Sea Grant/VIMS
Coakley	Bernard	University of Alaska
Codispoti	Lou	University of Maryland-Center for Environment
Coles	Mark	National Science Foundation
Collins	John	Woods Hole Oceanographic Institution
Colman	Steven	United States Geological Survey
Conlon	Dennis	National Science Foundation
Conway	Steven	Texas A&M University at Galveston
Cook	Susan	National Science Foundation
Corredor	Jorge	University of Puerto Rico
Costa	Daniel	University of California, Santa Cruz

Daly	Kendra	University of South Florida
Davidson	Margaret	NOAA Coastal Services Center
Davis	Curtiss	Naval Research Laboratory
Davis	Daniel	Monterey Bay Aquarium Research Institute
de Young	Brad	Memorial University of Newfoundland
deCharon	Annette	Bigelow Laboratory for Ocean Sciences
Delaney	John	University of Washington
DeLuca	Mike	Rutgers University
Detrick	Robert	Woods Hole Oceanographic Institution
Dewey	Richard	University of Victoria
Dhanak	Manhar	Florida Atlantic University
D'Hondt	Steve	University of Rhode Island
Diachok	Orest	Naval Research Laboratory
Dickey	Tommy	University of California, Santa Barbara
DiGiacomo	Paul	Jet Propulsion Laboratory
Donaghay	Percy	University of Rhode Island
Dorman	LeRoy	Scripps Institution of Oceanography
Drake	Tom	North Carolina State University in Raleigh
Duennebier	Fred	University of Hawaii
Dushaw	Brian	University of Washington
Edgington	Duane	Monterey Bay Aquarium Research Institute
Edwards	Nigel	University of Toronto
Eriksen	Charles	University of Washington
Feddersen	Falk	Scripps Institution of Oceanography
Fisher	Charles	Pennsylvania State University
Fornes	Bill	Consortium for Oceanographic Research and Education
Franks	Sharon	Scripps Institution of Oceanography
Fraser	Daniel	University of Manitoba
Freitag	Lee	Woods Hole Oceanographic Institution
Fryer	Patricia	University of Hawaii
Gallager	Scott	Woods Hole Oceanographic Institution
Garrett	John	NEPTUNE Canada
Gawarkiewicz	Glen	Woods Hole Oceanographic Institution
Geary	Edward	Colorado State University
Geyer	Rocky	Woods Hole Oceanographic Institution
Ghedira	Hosni	NOAA-CREST
Gilbert	Sherryl	University of South Florida
Glenn	Scott	Rutgers University

Goad	Linda	National Science Foundation
Goericke	Ralf	Scripps Institution of Oceanography
Grassle	Fred	Rutgers University
Griffin	Sean	University of Puerto Rico, Mayaguez
Groschel	Henny	University of Miami
Guinasso	Norman	Texas A&M University
Haidvogel	Dale	Rutgers University
Hailey	Michelle	Girl Scouts of America Research Institute
Halpern	David	Office of Science and Technology Policy
Hamilton	John	Monterey Bay Aquarium Research Institute
Hamner	Peggy	University of California, Los Angeles
Hamner	William	University of California, Los Angeles
Hanson	Alfred	University of Rhode Island
Hara	Tetsu	University of Rhode Island
Hart	Phil	Global Marine Systems Limited
Henry	Michael	University of California, Santa Barbara
Herren	Christy	Monterey Bay Aquarium Research Institute
Herrington	Tom	Stevens Institute of Technology
Hildebrand	John	Scripps Institution of Oceanography
Holt-Cline	Amy	University of New Hampshire
Howe	Bruce	University of Washington
Hussong	Don	Fugro Seafloor Surveys, Inc.
Isern	Alexandra	National Science Foundation
Itsweire	Eric	National Science Foundation
Jahnke	Richard	Skidaway Institute of Oceanography
Johnson	Michael	NOAA Office of Global Programs
Jumars	Peter	University of Maine
Juniper	Kim	Universite du Quebec a Montreal
Kappel	Ellen	Geosciences Professional Services, Inc.
Karson	Jeffrey	Duke University
Kasahara	Junzo	University of Tokyo
Kelley	Deborah	University of Washington
Kirby	Tracy	Ocean Institute
Kirkpatrick	Barbara	Mote Marine Laboratory
Kirkpatrick	Gary	Mote Marine Laboratory
Kirkwood	Bill	Monterey Bay Aquarium Research Institute
Kohler	David	Florida Environmental Research Institute
Kohut	Josh	Rutgers University
Kosro	Mike	Oregon State University
Kuroda	Yoshifumi	JAMSTEC
Lampitt	Richard	Southampton Oceanography Centre

Laske	Gabi	Scripps Institution of Oceanography
Leinen	Margaret	National Science Foundation
Lewis	Marlon	Dalhousie University & Satlantic, Inc.
Lilley	Marvin	University of Washington
Lindstrom	Eric	NASA
Locat	Jacques	Laval University
Lopez	Ramon	University of Puerto Rico, Mayaguez
Lozada	Ana	University of Puerto Rico, Mayaguez
Lukas	Roger	University of Hawaii
Luther	Doug	University of Hawaii
Luther	George	University of Delaware
Luther	Mark	University of South Florida
Maier	David	OGI School of Science and Engineering
Mann	David	University of South Florida
Martin	David	University of Washington
Massion	Gene	Monterey Bay Aquarium Research Institute
Matsumoto	George	Monterey Bay Aquarium Research Institute
McClure	Bob	Biosonics, Inc.
McDonnell	Janice	Rutgers University
McDougall	Carrie	NOAA
McGillis	Wade	Woods Hole Oceanographic Institution
McGuire	Maia	University of Florida Sea Grant
McPherson	Christopher	Ocean Design, Inc.
Meacham	Stephen	National Science Foundation
Meeson	Blanche	Ocean.US
Mendez	Flavio	Maryland Science Center
Mendez	Marla	University of Puerto Rico, Mayaguez
Mercer	James	University of Washington
Metaxas	Anna	Dalhousie University
Metz	Simone	Ocean.US
Midson	Brian	National Science Foundation
Mikada	Hitoshi	JAMSTEC
Mikhalevsky	Peter	SAIC
Mitzusawa	Kyohiko	JAMSTEC
Moeller	Greg	Bluefin Robotics Corporation
Moisan	John	NASA/GSFC
Moisan	Tiffany	NASA/GSFC
Moline	Mark	California Polytechnic State University
Morey	Steven	Florida State University
Morrison	John	North Carolina State University
Morrison	Ru	University of New Hampshire
Mullineaux	Lauren	Woods Hole Oceanographic Institution
Mullison	Jerry	RD Instruments
Murphy	David	Sea-Bird Electronics, Inc.
Murray	Laura	University of Maryland-Center for Environment
Murty	Vadlamani	National Institute of Oceanography
Musgrave	Dave	University of Alaska
Newman	Robert	Scripps Institution of Oceanography
Nolet	Guust	Princeton University
Nystuen	Jeffrey	University of Washington
O'Donnell	James	University of Connecticut
Oechel	Walt	San Diego State University
Ojeda	German	Coastal Carolina University
Olsen	Margaret	Southeast Center for Ocean Sciences Education
Oltman-Shay	Joan	NorthWest Research Associates
Orcutt	John	Scripps Institution of Oceanography
Orrico	Christina	University of California, Santa Barbara
Pagan	Lopez	Francisco University of Puerto Rico
Paluszkiewicz	Terri	Office of Naval Research
Paull	Charles	Monterey Bay Aquarium Research Institute
Penrose	Nancy	University of Washington
Perry	Mary Jane	University of Maine
Person	Roland	Ifremer
Pettigrew	Neal	University of Maine
Phibbs	Peter	Mallin Consultants Ltd.
Pinckney	James	Texas A&M University
Pinkel	Rob	Scripps Institution of Oceanography
Pitman	Lisa	University of Miami
Pompa	Jon	Scripps Institution of Oceanography
Porter	Michael	SAIC
Pouliquen	Sylvie	Ifremer
Purdy	Michael	Lamont-Doherty Earth Observatory
Quigg	Antonietta	Texas A&M University at Galveston
Rack	Frank	Joint Oceanographic Institutions
Rashid	Harunur	Massachusetts Institute of Technology
Raybould	Keith	Monterey Bay Aquarium Research Institute
Reichert	Konstanze	OceanWaveS
Richardson	Tammi	Texas A&M University
Richie	Morgan	Ocean Institute
Robigou	Veronique	University of Washington
Roesler	Collin	Bigelow Laboratory for Ocean Sciences
Ross	Sarah	NOAA
Rudnick	Daniel	Scripps Institution of Oceanography
Sarrazin	Jozee	Ifremer

Sautter	Leslie	College of Charleston
Savidge	Dana	Skidaway Institute of Oceanography
Schmidt	Henrik	Massachusetts Institute of Technology
Schoch	Carl	Prince William Sound Science Center
Schoenberg	Judy	Girl Scouts of America Research Institute
Schofield	Oscar	Rutgers University
Schultz	Adam	Oregon State University
Send	Uwe	IfM Kiel
Seymour	Richard	Scripps Institution of Oceanography
Shaheen	Nazeeh	NAUTRONIX MariPro INC
Shaw	Timothy	University of South Carolina
Sheremet	Vitalii	University of Rhode Island
Shimmield	Graham	Scottish Association for Marine Science
Sibenac	Mark	Monterey Bay Aquarium Research Institute
Simons	Frederik	Princeton University
Singh	Hanumant	Woods Hole Oceanographic Institution
Slutskin	Rochelle	Anne Arundel County Public Schools
Smarr	Larry	University of California, San Diego
Smith	David	United States Naval Academy
Smith	Raymond	University of California, Santa Barbara
Snelgrove	Paul	Memorial University of Newfoundland
Snyder	David	Gallaudet University
Soloviev	Alexandre	NOVA Southeastern University
Sosik	Heidi	Woods Hole Oceanographic Institution
Spector	Barbara	University of South Florida
Spence	Lundie	SC Sea Grant Consortium
Spiess	Fred	Scripps Institution of Oceanography
Spranger	Mike	University of Florida
Stakes	Debra	Monterey Bay Aquarium Research Institute
Stephen	Ralph	Woods Hole Oceanographic Institution
Strub	Ted	Oregon State University
Swart	Peter	University of Miami
Tarits	Pascal	UBO/IUEM
Terrill	Eric	Scripps Institution of Oceanography
Thigpen	Jack	NC Sea Grant
Thomas	Carrie	North Carolina State University
Thurnherr	Andreas	Lamont-Doherty Earth Observatory
Thurston	Sidney	NOAA
Tivey	Maurice	Woods Hole Oceanographic Institution
Tivey	Meg	Woods Hole Oceanographic Institution
Tolstoy	Maya	Lamont-Doherty Earth Observatory
Toomey	Doug	University of Oregon
Trask	Jennifer	Monterey Bay Aquarium Research Institute
Trees	Charles	San Diego State University
Tweedie	Sara	Tweedie & Associates
Vaillancourt	Robert	Lamont-Doherty Earth Observatory
Vernon	Frank	Scripps Institution of Oceanography
Visbeck	Martin	Lamont-Doherty Earth Observatory
Wagner	Bob	Consortium for Oceanographic Research and Education
Walker	Shelby	Naval Research Laboratory
Webb	Spahr	Lamont-Doherty Earth Observatory
Weller	Robert	Woods Hole Oceanographic Institution
Wells	Judith	Old Dominion University
Werner	Cisco	University of North Carolina
Wetzell	Lauren	University of South Florida
Whelan	Jean	Woods Hole Oceanographic Institution
Wilcock	William	University of Washington
Williams	Robin	University of Puerto Rico-Mayaguez
Winter	Amos	National Science Foundation
Worcester	Peter	Scripps Institution of Oceanography
Wright	Don	VIMS
Wunsch	Carl	Massachusetts Institute of Technology
Yoder	Ellen	Consortium for Oceanographic Research and Education
Yoder	James	National Science Foundation
Yoerger	Dana	Woods Hole Oceanographic Institution
Zappa	Christopher	Lamont-Doherty Earth Observatory
Zika	Rod	University of Miami
Zumberge	Mark	Scripps Institution of Oceanography

Appendix 2

Agenda

3 January 2004	
3:00-6:00	**Registration**
6:00-8:30	**Kickoff Reception**
4 January 2004	
8:15-9:00	**Plenary** 8:15-8:30: Welcome - Meg Tivey and Oscar Schofield 8:30-8:50: NSF Ocean Observatories Initiative - Margaret Leinen 8:50-9:00: Anticipated Outcomes - Meg Tivey and Oscar Schofield
9:00-12:30	**Plenary: SCIENCE OVERVIEWS** The talks will touch on major science themes. Speakers (20 min. + 5 min. for questions) Robert Bigidare: Non-Equilibrium Ecosystem Dynamics and Ocean Biogeochemistry Bob Detrick: Earth Structure and Dynamics Carl Wunsch: Ocean Dynamics and Global Climate Dave Musgrave: Biophysical Interactions in Coastal Regions Deb Kelley: Fluid-Rock Interaction and Its Influence on Life Dale Haidvogel: Relationship of Numerical Models to ORION
12:30-1:30	**Lunch on own**
1:30-2:45	**Plenary: TECHNOLOGY OVERVIEWS** Speakers (15 min. + 5 min. for questions) Tommy Dickey: Overview - Where We Have Been and Where We Are John Delaney: Integrated Possibilities Gene Massion: Cable Development/Re-use/Test Cables
2:45-3:45	**Plenary: EDUCATION** Speakers (15 min. + 5 min. for questions) Janice McDonnell: K-12 Education and use of Observatory Information Ed Geary: GLOBE (Global Learning and Observations to Benefit the Environment) Systemic Efforts in K-12 Education Judy Schoenberg: Engaging Girls & Teens in Science and Technology Careers: What the Research Tells Us
3:45-4:00	**Plenary: NATIONAL AND INTERNATIONAL PROGRAMS OVERVIEW** Overview of solicited papers/posters of other national programs and international programs - Meg Tivey and Oscar Schofield
5:30-6:15	**Plenary: AGENCY OVERVIEW PANEL** Panel with agency representatives to discuss broader ocean observing activities. Panelists: H. Lawrence Clark (NSF), Michael Johnson (NOAA), Eric Lindstrom (NASA), Larry Atkinston (Ocean.US), Teresa Paluszkiewicz (ONR)
6:15-8:00	**Social Hour with posters and education displays**
5 January 2004	
8:30-9:00	**Plenary: Review of any concerns by the participants**
9:00-9:30	**Plenary: Instructions to Working Groups**

9:30–1:00	**Break into working groups.** Work through checklist. Each group will have representatives from deep-sea, regional, coastal, and some engineers and educators. The groups in considering their question should appreciate a distributed observation network that would exist with both fixed and relocatable assets.
	9:30-10:30: Education/Outreach and Engineering working groups will meet separately then disperse to participate in the science working groups as the plans are formulated, and meet back as a group as ideas evolve.
Free Afternoon:	**Lunch on own**
	Moderators/Rapporteurs meet with Steering Committee. We have freed up afternoons so that groups will not be confined to indoors. The goal is to promote lots of brainstorming and discussion.
4:30-5:30	**Plenary Session – Review of progress made**
5:30-7:00	**Working Groups**
6 January 2004	
8:30-9:45	**Plenary: Review of any concerns by the participants** Chris Barnes: Brief Overview of NEPTUNE Canada Scott Gallager: Integrated Sensor Systems
9:45-1:00	**Break into Working Groups**: Continue BIG question discussions, working through checklist. Again, an emphasis should include all relevant components of the OOI to address the big questions. Specifics today should focus on how to conduct the experiments.
	E/O and Engineering group meets together then disperses to science working groups.
	11:30-1:00: Global, Regional, and Coastal representatives meet to discuss temporal and spatial scales required as well as potential locations.
Free Afternoon	Lunch on own
	Moderators/Rapporteurs meet with Steering Committee.
4:30 - 7:00	Plenary Session Review of Working Group progress.
7 January 2004	
8:30-10:15	**Plenary: Review of any concerns by the participants** Blanche Meeson: Report on Education Group Progress Hitoshi Mikada: Japanese Efforts in Cabled Observation and International Cross-Program Cooperation Roland Person: Observatory Developments in Europe Steven Bohlen: Structure of IODP Larry Smarr: Cyberinfrastructure
10:15-12:00	**Break into working groups:** Continue BIG question discussions, finalizing plan and finishing answering questions on checklist.
	9:00-10:00: Global, Regional, and Coastal group meets.
	E/O and Engineering Groups meet separately then disperse to science working groups.
12:00-3:00	**Moderators/Rapporteurs meet with Steering Committee.**
3:00-5:00	**Brief Plenary** Jim Bellingham: Report on Progress of Engineering Working Group
	Break into Working Groups: Each of the groups (including E/O group) should prepare an overview and overall strategy. The moderators/rapporteurs and SC should assimilate the reports for morning presentations.
6:00	**Evening party**
8 January 2004	
8:30-9:00	**Plenary: Review of any concerns by the participants**
9:00-12:00	**Plenary: Overview of the BIG questions.** Which ones are we ready to tackle now? Which can we answer in 20 years? Questions by the crowd? Discuss consensus statements and sensor suites, questions.
Marching orders	

Appendix 3

Posters

Last Name	First Name	Institution	Poster Title
Ammerman	Jim	Rutgers University	*In Situ* Measurement of Microbial Enzyme Activities at Ocean Observatories
Atkinson	Larry	Ocean.US/Old Dominion	The Integrated Ocean Observing System
Bane	John	University of North Carolina	Airborne Oceanic and Atmospheric Measurements for Coastal Observing: The UNOLS Perspective
Baptista	Antonio	Oregon Health & Science University	CORIE: A Coastal-margin Observatory for the Columbia River, Since 1996
Barnard	Andrew	WET Labs	Bio-optical Instrumentation for Use on Long-term Ocean Observing Systems
Beardsley	Robert	Woods Hole Oceanographic Institution	An Integrated Coastal Ocean Modeling System
Bemis	Karen	Rutgers University	Acoustic Imaging of Seafloor Hydrothermal Flow Regimes
Berger	Jon	Scripps Institution of Oceanography	Providing Communications and Networking for the ORION Fleet of Moored Ocean Observatories.
Bissett	Paul	Florida Environmental Research Institute	The Integration of Airborne, Satellite, and AUV Technologies for the Near Real Time Analysis of the Coastal Environment
Bohnenstiehl	Del	Lamont-Doherty Earth Observatory	Monitoring Geological, Biological and Anthropogenic Processes Using Hydroacoustic Sensors
Brey	James	University of Wisconsin Fox Valley, American Meteorological Society	Datastreme Ocean: A New Distance-Learning Course for Precollege Teachers on the Basics of Oceanography
Cannat	Mathilde	Institute de Physique do Globe de Paris-CNRS	Recent Developments of the MOMAR Project
Clark	Vicki	Virginia Sea Grant/VIMS	The BRIDGE
Collins	John	Woods Hole Oceanographic Institution	A Test Deployment of a Deep-Water, Acoustically-Linked, Moored-Buoy Observatory: Preliminary Results
Costa	Daniel	University of California, Santa Cruz	Tagging of Pacific Pelagics (TOPP): Using Organisms as Bioprobes for the Ocean Environment
Dam	Hans	University of Connecticut	Highlights of the FRONT Program, a Multi-institutional Partnership Conducted off Long Island Waters
Delaney	John	University of Washington	NEPTUNE: A Regional Cabled Observatory in the Northeast Pacific
Dewey	Richard	University of Victoria	The VENUS Project
Dhanak	Manhar	Florida Atlantic University	AUVs in Conjunction with Surface Current Radar for Observing Meso-scale to Fine Scale Turbulence in a Subtropical Coastal Environment During the Passage of a Cold Front
Diachok	Orest	Naval Research Laboratory	An Introduction to Bioacoustic Absorption Spectroscopy (BAS)
Dorman	LeRoy	Scripps Institution of Oceanography	An Implosive Seismic Source Suitable for Seafloor Use
Duennebier	Fred	University of Hawaii	Re-Use of Retired Optical Cable Systems for Ocean Observatories

Edgington	Duane	Monterey Bay Aquarium Research Institute	SENSORS: Ocean Observing System Instrument Network Infrastructure
Edson	James	Woods Hole Oceanographic Institution	CBLAST 2003 Experiment at the Martha's Vineyard Coastal Observatory (MVCO)
Fisher	Charles	Pennsylvania State University	The US National Science Foundation Ridge 2000 Program
Fryer	Patricia	University of Hawaii	A Cabled Regional Seafloor Observatory on the Type Nonaccretionary Convergent Plate Margin
Gallager	Scott	Woods Hole Oceanographic Institution	The Autonomous Vertically Profiling Plankton Observatory
Gavrilov	Alexander	Curtin University of Technology	Achievements and a Potential Role of Underwater Acoustics in Studying Large-Scale Changes in the Arctic Ocean
Gawarkiewicz	Glen	Woods Hole Oceanographic Institution	Scientific Issues and Background for a Potential Observatory in the Middle Atlantic Bight
Geyer	Rocky	Woods Hole Oceanographic Institution	Scientific Potential of a Coastal Observatory: The Need for Improved Temporal and Spatial Aperture
Guinasso	Norman	Texas A&M University	Texas Automated Buoy System
Hankin	Steve	NOAA Pacific Marine Environmental Laboratory	The US Integrated Ocean Observing System (IOOS) Plan for Data Management and Communications (DMAC)
Hildebrand	John	Scripps Institution of Oceanography	Long-Term Monitoring for Marine Mammals Using Passive Acoustics
Howe	Bruce	University of Washington	Science Enabled by Ocean Observatory Acoustics
Howe	Bruce	University of Washington	Sensor Networks for Ocean Observatories
Kelley	Deborah	University of Washington	The Endeavour Observatory
Kirkpatrick	Gary	Mote Marine Laboratory	Detecting Harmful Algae Using Autonomous Underwater Vehicles
Kirkwood	Bill	Monterey Bay Aquarium Research Institute	Beyond Climate: Cabled Experiments to Simulate the Emerging High CO_2 Ocean
Kohut	Josh	Rutgers University	An HF Radar Network for the NorthEast Ocean Observing System (NEOS)
Lampitt	Richard	Southampton Oceanography Centre	ANIMATE Program
Lewis	Marlon	Dalhousie University and Satlantic, Inc.	Ocean Observatories We Have Known
Lilley	Marvin	University of Washington	Using *In Situ* Resistivity Probes to Measure Long-Term Chloride Trends in Hydrothermal Fluids
Luther	George	University of Delaware	*In Situ* Voltammetry Monitors Chemical Redox Parameters in Diverse Marine Environments
Luther	Mark	University of South Florida	An Integrated Observing and Modeling System for Tampa Bay
Mann	David	University of South Florida	Passive Acoustic Detection of Spawning Fishes
Mercer	James	University of Washington	Acoustic Remote Sensing of Large-Scale Temperature Variability in the North Pacific Ocean
Mikada	Hitoshi	JAMSTEC	Earthquake Monitoring Cabled Observatory at a M8 Earthquake
Mitzusawa	Kyohiko	JAMSTEC	Deep Current Measurements Using the Cabled Observatories in the Northwest Pacific
Moisan	Tiffany	NASA/GSFC	The Development of a Compact Harmful Algal Bloom Observing System
Moline	Mark	California Polytechnic State University	AUV/New Sensor Deployments off the Coast of California Examining Physical Forcing on Ecosystem Dynamics
Morrison	Ru	University of New Hampshire	Coastal Ocean Observation and Analysis (COOA)

Murray	Laura	University of Maryland-Center for Environmental Sciences	Observing Systems and Education: Pilot Course for Teachers
Newman	Robert	Scripps Institution of Oceanography	Immersive Exploration of 3-D Datasets with the Geowall - Applications to Ocean Observatories
Nystuen	Jeffrey	University of Washington	Passive Acoustic Measurements of Oceanic Rainfall and Wind Speed
O'Donnell	James	University of Connecticut	HF RADAR Based Coastal Current Estimates for Search and Rescue Applications
Pettigrew	Neal	University of Maine	The Gulf of Maine Ocean Observing System: A Multi-Use System for Oceanographic Research, Public Outreach, and Marine Safety
Pinkel	Rob	Scripps Institution of Oceanography	The WIREWALKER, an Inexpensive Profiling Float Powered by Ocean Waves
Proshutinsky	Andrey	Woods Hole Oceanographic Institution	Ice-Tethered Instrument for Monitoring the Arctic Ocean Upper 500-800 m Structure with 1 Meter Resolution via Satellite Daily
Roesler	Collin	Bigelow Laboratory for Ocean Sciences	Seasonal Transitions in Ecosystem Structure in the Gulf of Maine as Determined from the Gulf of Maine Ocean Observing System (GoMOOS) Optical Sensing Program
Rudnick	Daniel	Scripps Institution of Oceanography	Autonomous and Lagrangian Platforms and Sensors (ALPS)
Sarrazin	Jozee	Ifremer	The Exocet/D Project : an European Initiative Towards the Establishment of a Research Program Dedicated to Long-term Monitoring of Deep Ocean Ecosystems
Sautter	Leslie	College of Charleston	The Transects Program
Sibenac	Mark	Monterey Bay Aquarium Research Institute	AUV Docking for MBARI's Ocean Observing Systems
Simons	Frederik	Princeton University	Listening to Earthquakes with Hydrophones Mounted on SOLO Floats
Smith	David	United States Naval Academy	An Overview of the Educational Programs of the American Meteorological Society
Soloviev	Alexandre	NOVA Southeastern University	Environmental Array and Data Analysis (SFOMC)
Sosik	Heidi	Woods Hole Oceanographic Institution	Time Series Monitoring of Coastal Phytoplankton: Abundance and Growth Rates from Submersible Flow Cytometry
Stakes	Debra	Monterey Bay Aquarium Research Institute	Instrumentation, Deployment Methodology and Strategy for a Long Term Seismic Array on the Endeavour Segment of the Juan de Fuca Ridge
Stephen	Ralph	Woods Hole Oceanographic Institution	Global Siting Plan for Geophysical Observatories in the International Ocean Network
Thurnherr	Andreas	Lamont-Doherty Earth Observatory	Oceanographic and Topographic Influences on Dispersal of Hydrothermal Vent Species
Vernon	Frank	Scripps Institution of Oceanography	Applications of ROADNet Project to Ocean Observatories
Weller	Robert	Woods Hole Oceanographic Institution	Ocean Reference Stations
Williams	Robin	University of Puerto Rico-Mayaguez	Wave Observation System for the Puerto Rican Coastline
Zappa	Christopher	Lamont-Doherty Earth Observatory	Tower-Based and Airborne Infrared Imagery Measurements Detailing Near-Surface Processes
Zika	Rod	University of Miami	A Model for a Global Autonomous Oceanographic and Meteorological Monitoring Network

Appendix 4

Working Group Check List

1. What are the most exciting opportunities provided by ORION? Consider all potential assets, and not solely cables and moorings.

2. Why can't we address this using traditional assets and techniques?

3. What are the spatial and temporal scales required?

4. What are the synergistic needs beyond the fixed infrastructure of the OOI (For example, will site surveys be needed and what would these surveys include?).

5. Identify priority measurements and parameters needed to address science being identified
   a. What measurement capabilities are needed?
   b. What technology currently exists?
   c. What needs to be developed?
   d. Which measurements would be considered part of a core sensor suite (Basic engineering and scientific instruments essential to the functioning of the observatory and will serve basic research; will vary by the class of observatory and the scientific objectives of a particular node.)
   e. What sensors/instruments should be considered community assets? (Specialized instruments critical to the longer-term scientific objectives of a particular node; proven and reliable; a wide range of researchers.)
   f. What sensors/instruments would be from individual PIs? (New, developmental, or specific to a single study or experiment.)

6. What scientific issues require augmentation (e.g., from other international programs)?

7. How do we entrain the scientific community?

8. What are the education/outreach possibilities?

9. What are the data policy/management/archive needs?

10. Time line for addressing question/experiment?

11. Concrete examples: 5-year, 20-year, and kick-off projects.

Appendix 5

Acronyms

AAAS .... American Association for the Advancement of Science
AABW................. Antarctic Bottom Water
AAIW.................. Antarctic Intermediate Water
ACORKs .... Advanced borehole seals
ADCP.................. Acoustic Doppler Current Profiler
ADV .... Acoustic Doppler Velocimeter
ALPS.................... Autonomous and Lagrangian Platform and Sensors
ATP...................... Adenosine Triphosphate
AUV .... Autonomous Underwater Vehicle
BOD .... Biochemical Oxygen Demand
CCS...................... California Current System
CDOM .... Colored Dissolved Organic Matter
CLIVAR .... Climate Variability and Predictability Program
CMB .... Core-Mantle Boundary
CoOP................... Coastal Ocean Processes
CTD..................... Conductivity-Temperature-Depth instrument
DEOS .... Dynamics of Earth and Ocean Systems
DIDSON .... Dual-frequency Identification Sonar
DMS .... Dimethyl Sulfide
ECOHAB .... Ecology and Oceanography of Harmful Algal Blooms Program
ENSO .... El Niño-Southern Oscillation
EPR...................... East Pacific Rise
ESONET .... European Seafloor Observatory Network
ESP....................... Environmental Sample Processor
GEOHAB............ Marine Geological and Biological Habitat Mapping
GLOBEC............. Global Ocean Ecosystem Dynamics
GOOS.................. Global Ocean Observing System
HAB..................... Harmful Algal Bloom
HOV .... Human-Operated Vehicle
HPLC .... High-Performance Liquid Chromatography
ICES..................... International Council for the Exploration of the Sea
IMBER .... Integrated Marine Biogeochemistry and Ecosystem Research
IOCCP .... International Ocean Carbon Coordination Project
IODP .... Integrated Ocean Drilling Program
IOOS .... Integrated Ocean Observing System
JAMSTEC .... Japan Marine Science & Technology Center
JFR....................... Juan de Fuca Ridge
JGOFS .... Joint Global Ocean Flux Study
LISST .... Laser In-Situ Scattering and Transmissometry instrument
MARGINS........... A geology and geophysics program studying continental margins

MASZP .... Moored Automated Serial Zooplankton Pumps
MBL...................... Marine Boundary Layer
MEMS .... Micro-Electro Mechanical Systems
MERHAB............. Monitoring and Event Response for Harmful Algal Blooms
MOC .... Meridional Overturning Circulation
MOMAR.............. MOnitoring on the Mid-Atlantic Ridge
MPA .... Marine Protected Areas
MREFC .... NSF's Major Research Equipment and Facilities Construction
NADW .... North Atlantic Deep Water
NAO .... North Atlantic Oscillation
NASA .... National Aeronautics and Space Administration
NEMO.................. New Millennium Observatory
NERR .... National Estuarine Research Reserve
NOAA .... National Oceanic and Atmospheric Administration
NOAA/PMEL ..... NOAA/Pacific Marine Environmental Laboratory
NSF....................... National Science Foundation
OBS....................... Optical Backscatter Sensors
OceanSITES .... International Ocean Timeseries Observatory Network
ODP...................... Ocean Drilling Program
ONR .... Office of Naval Research
OOI .... Ocean Observatory Initiative
OOPC................... Ocean Observing Panel for Climate
ORION................. Ocean Research Interactive Observatory Networks
OSSE..................... Observing System Simulation Experiments
PDO .... Pacific Decadal Oscillation
PICES .... The North Pacific Marine Science Organization
PMEL .... Pacific Marine Environmental Laboratory
PNW..................... Pacific Northwest
POGO .... Partnership for Observation of the Global Oceans
RIDGE2000......... Multidisciplinary program studying mid-ocean ridges
SAM .... Southern Annual Mode
SCOTS .... Scientific Cabled Ocean Time Series
SOLAS.................. Surface Ocean-Lower Atmosphere Study
TAPS-6................. Acoustic instrument
ULVZ.................... Ultra Low Velocity Zone
VPS....................... Vertical Profiling System

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ORION

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