NEW SEAFLOOR OBSERVATORY NETWORKS IN SUPPORT OF OCEAN SCIENCE RESEARCH

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***Abstract* – Ocean science encompasses young and rapidly evolving disciplines. The approaches needed to observe and experiment with the physical, chemical, biological and geological processes in our world's oceans have changed considerably over the past two decades. There is increasing emphasis on research involving long-term experiments and sustained time-series observations. This trend requires substantially different infrastructure to continue into the 21st century the rapid rate of scientific progress that began in the early 1960's.**

Several pilot projects have successfully installed seafloor observatories using newly developed junction boxes and fiber-optic cable protocols. Technology development efforts have also advanced moored and relocatable buoys, instrumentation, sensors, and communication capabilities. In response to increasing demands by researchers for sustained observations and capitalizing on recent advances in technology, an initiative has been developed for providing the basic infrastructure necessary for implementing an integrated system of ocean observatories. The proposed system has three elements: 1) a lithospheric plate-scale observatory consisting of interconnected sites on the seafloor that span several geological and oceanographic features and processes, 2) several relocatable deep-sea observatories based around a system of buoys, and 3) an expanded network of coastal observatories.

INTRODUCTION

The ocean sciences are shifting from an intermittent expeditionary mode of identifying "what's out there" to a sustained, *in situ* experimental mode of exploring well-defined natural systems in the time domain. The shift arises in part from the rapidly expanding developments in the computational, robotic, communications, and sensor capabilities and in part from a maturation of the natural sciences that involves a growing awareness of process complexity and interactive dynamics in many systems.

Ocean observatories, which capitalize on recent technological developments, can enable the production of unique sustained time-series data sets, impossible to record today. The new perspectives these data will provide for dynamic ocean interactions will stimulate new paradigms in the way we think about the ocean's biological, chemical, physical and geological processes.

Numerous reports prepared by members of the academic community and other partners have established the intellectual basis and defined the need for an ocean observatory initiative. In July 2000, the National Research Council's (NRC) Ocean Studies Board published a report entitled "Illuminating the Hidden Planet: The Future of Seafloor Observatory Science" [1]. Two findings included the statements that "*seafloor observatories have significant scientific merit and they will complement and extend current scientific approaches*" and "*the extent to which seafloor observatories will address future requirements for conducting multidisciplinary research is very significant, and essential in some fields.*" The NRC lead recommendation was that the National Science Foundation "*should move forward with the planning and implementation of a seafloor observatory program.*"

"Ocean Sciences at the New Millennium," a report prepared by the Ocean Sciences Decadal Committee and published in April 2001, reinforces the critical need for enhancing observatory science [2]. The report, developed with extensive community input, identifies key research opportunities for the entire field of ocean sciences in the coming decade and beyond. One of its concluding recommendations declares "*the lack of extensive, more-or-less continuous time-series measurements in the oceans is probably one of the most serious impediments to understanding of long-term trends and cyclic changes in the oceans and in global climate, as well as episodic events such as major earthquakes, volcanic eruptions or submarine landslides. We recommend strong support for the development, deployment and maintenance of long-term observing systems.*"

Other studies and reports that underscore the scientific importance of being able to make relevant time-series observations for basic research include the Ocean Seismic Network Pilot Experiment and "Toward a U.S. Plan for an Integrated, Sustained Ocean Observing System," which outlines a plan for moving from pilot efforts to a comprehensive, large-scale ocean observing system [3, 4].

SCIENCE DRIVERS

The National Science Foundation's Division of Ocean Sciences is seeing an increasing proportion of its research base going towards projects that require sustained observations. This evolving scientific trend is expected to continue.

The science topics and themes that can be tackled using ocean observatory capabilities span a wide range of studies. The following paragraphs outline a set of scientific issues for which ocean observatories could enable major breakthroughs by using new technology and innovative experimental approaches. The examples are illustrative rather than inclusive and are consistent with numerous published community reports, including those identified above.

A. Ecological Characterizations

It was recently suggested that the deep sea might contain as many as ten million species, a level of diversity that rivals that in tropical rainforests and coral reefs. Interdisciplinary studies of patterns and controls on biological diversity, with traditional sampling conducted within the context of cable-facilitated measurements of dynamic and spatially varying environmental parameters, may contribute to understanding the ecology of the deep sea.

B. *Water Column Studies*

Over the past few decades, our knowledge of ocean circulation and variability has advanced significantly despite the fact that nearly all *in situ* ocean observing systems have been limited in their spatial and temporal coverage (i.e., single-point moorings, regional networked moorings, and sparsely distributed surface drifters and subsurface floats). Although satellite remote-sensing technology has progressed to a point at which almost all *surface* variables can be routinely measured from space, the oceanic interior has been largely unsampled, except in a few small coastal regions. Recent technological advances in sensors and observing systems on the one hand, and numerical models and data assimilation on the other, have begun to change this situation. Observing networks combining remote sensing datasets with extensive subsurface fields obtained from both fixed and autonomous platforms are beginning to provide new insights. Modern communication systems and the World Wide Web enable real-time reporting and distribution of these data. And finally, numerical ocean circulation models, and associated techniques of data assimilation, now allow meaningful forecasts of future states of the physical circulation, and have begun to provide hindcasts and forecasts of coupled chemical and biological processes.

C. Upwelling and Productivity

Coastal upwelling occurs on the coasts of most continents, all of which are areas of enhanced biological productivity. Many aspects of coastal upwelling are dependent on the local combination of dynamic, physical, and biological processes, all of which are characterized by dramatic temporal and spatial variability and are not well constrained by satellite, shipboard, or self-contained mooring observations. Cabled observatories are capable of examining the multiple linkages between the disparate, successional processes that influence the timing and strength of coastal upwelling and the subsequent influence on marine ecosystem structure and function. These studies would provide the scientific linkage between primary and secondary productivity and fish larval recruitment, providing unique information on the natural variability of regional fish stocks.

D. Organic Carbon Fluxes

Over the past two decades, oceanographers have gained an appreciation for temporal variability in the flux of organic material to the seafloor and for seasonal processes such as growth, reproduction, and recruitment in benthic invertebrates, but compelling evidence for the link between productivity and these processes has been elusive. The dynamics of this process are important in understanding CO_2 sequestration in the sediments and the role of the oceans in ameliorating atmospheric CO_2 buildup. Cable-facilitated measurements of organic flux and other environmental parameters can be combined with traditional methods of sampling organisms to resolve the dynamics of supply and response under a variety of seafloor conditions.

E. Sediment Transport

Sediment transport along and across the shelf and into the deep ocean can be quantified as a function of the processes that drive such systems. Large fluxes of sediment laden with carbon and anthropogenic chemicals cross the continental shelf and slope in a highly episodic fashion during major storms, but the mechanisms are poorly understood. A more complete understanding of water-column physics, chemistry, and biology would permit the links between primary productivity, fisheries, marine mammal migration, and deep-sea ecology to be addressed. Long-term cabled observatories are well suited to make substantial advances in our knowledge of the rates and mechanisms of mass flux to the deep ocean.

F. Fluids, Chemistry, and Life in the Oceanic Crust

One of the most exciting scientific problems that can be addressed using observatory science concerns the nature of the subsurface biosphere. This extreme environment below the seafloor is thought to contain a population of dormant microbes that periodically undergo a population explosion resulting from input of heat and volatiles into the crust from episodic seismic events. In addition to the ridge crest and flanks, a population of live microbes is also thought to exist in the extreme environment of subduction zones sustained by either continuous or episodic input of energy and nutrients. Similarly, the dynamics of gas hydrate formation and dissociation, especially in response to perturbations produced by tectonic cycles or global warming, is a problem of current interest that could be addressed by observatory science.

G. Spreading Centers

Seafloor spreading is an intermittent, shifting balance among strain accumulation, normal faulting, and volcanic accretion. The relative importance of tectonism and plutonism varies in both time and space and reflects the interplay between magma supply from the mantle and heat loss to the ocean, which is dominated by vigorous hydrothermal circulation. Along mid-ocean ridges, hydrothermal fluids transport dissolved materials, and the chemical potential energy produced as they rise and mix with seawater sustains diverse communities of chemosynthetic life forms, both on the seafloor and in subsurface pore spaces. Periodic eruptive events flush existing hydrothermal fluids from the crust and constitute natural perturbation experiments. These events may cause short-lived bursts of very vigorous hydrothermal venting and lead to spectacular microbial blooms. Fault motions and cracking events induced by thermal contraction may open new pathways for circulating fluids to enter hot rock, thus temporarily increasing hydrothermal fluxes and changing the chemistry. It is extremely difficult to assemble the full array of instrumentation necessary to monitor all aspects of these interrelated systems at the same time. Stand-alone experiments are significantly shorter than the time scales of the volcanic and tectonic cycles responsible for seafloor spreading. A cable-supported natural laboratory would provide the infrastructure necessary to concentrate multidisciplinary observations at a few key sites on appropriate time scales. It would allow scientists to observe events in their entirety, adapting their experiments in real-time to respond to changes in the system.

H. Subduction Processes

Subduction zones host a wide variety of fundamental and important geological processes. For example, intra-plate slippage along subduction thrusts is the cause of the world's largest tsunami-generating earthquakes. Our understanding of the time dependence of the processes affecting the quakes is poor for the simple technological reason that comprehensive time-series observations at long time scales are difficult to obtain at sea, and many of the most significant processes are only active well offshore. Further progress will require decadal time-series observations made at deep ocean sites. Cables can provide adequate and constant power for instruments, and they can facilitate contemporaneous measurements of disparate variables over long time scales, which is essential to their characterization and understanding. Since subduction processes are episodic, a cabled observatory would provide the capability to modify sampling and measurement protocols in response to changes.

I. Plate Interiors

Oceanic plates occupy two thirds of Earth's surface. Consequently intra-plate processes are of global importance. For example, much of Earth's heat is lost through cooling over entire lithospheric plates. Stresses within them provide critical clues about the various forces that drive and resist plate motion. Hydrothermal circulation on mid-ocean ridge flanks is responsible for the exchange of large amounts of heat and chemical constituents between the oceans and the oceanic crust, and may fuel thermophilic microbes that take advantage of the chemical potentials in this dynamic regime. Many of the questions that remain unanswered about intra-plate processes and structure can be addressed well, and in some cases only, through observatory studies. A transect of observatory sites that crosses an oceanic plate from shore, and uses existing drill holes for long-term hydrologic, seismic, and related studies, would allow many of these questions to be addressed. A cable link to shore is a central infrastructure requirement for such experiments.

J. Seismology and Magnetics

Large gaps exist in the global network of seismic stations that cannot be filled with island stations, particularly in the eastern Pacific and Southern Oceans. Improved spatial sampling provided by buoyed observatories supporting broadband seismometers at strategically located ocean sites would provide much improved tomographic imaging of the structure of the lower mantle (especially in the Southern Hemisphere), the core-mantle boundary, and the role of subducting slabs and plumes in deep mantle circulation.

K. Real-Time Regional Modeling and Forecasting

The ocean is intermittent, eventful, and episodic. It is an essentially turbulent fluid whose circulation is characterized by a myriad of dynamical processes occurring over a vast range of nonlinearly interactive scales in space and time. Ocean modeling and forecasting are essential for effective and efficient coastal zone management, scientific research, and maritime operations. Observations are used to initialize dynamical forecast models, and further observations are continually assimilated into the models as the forecasts advance in time. A network of coastal observatories with the ability to make a wide range of measurements and enable adaptive sampling of the observations can have significant impact on the accuracy and timeliness of regional coastal models and forecasts.

EDUCATION AND PUBLIC OUTREACH OPPORTUNITIES

In addition to opening up an array of research opportunities, a system of networked seafloor observatories that would allow real-time access to observe and study the dynamic processes of the marine world holds great promise for capturing the imagination of the public through formal and informal education activities. Data from the network would flow in real-time via the Internet to land-based laboratories, classrooms, and living rooms around the world. Scientists, students, decision makers, and the general public could interact with the network to gain new understanding of earthquakes, tsunamis, fish stock assessment, marine mammal populations, metal and hydrocarbon deposits, and human influences on ocean and climate systems.

Direct observational capabilities, which include access to a wide variety of sensor packages and robotic vehicles via the Internet, would be significantly more engaging than turning the pages of a textbook. By capitalizing on real-time communication with an entire earth-ocean system, this new approach to studying the oceans could be used to stimulate human creativity and develop fundamentally new approaches to scientific inquiry.

TECHNOLOGY DEVELOPMENT AND PILOT OBSERVATORIES

In response to the shift in the conduct of ocean science research, recommendations from community planning activities, and strong proposals, NSF and other agencies have invested in the design, development and implementation of prototype observatories and associated sensor systems. Additionally, NSF has developed an Ocean Observatories Initiative (OOI) for possible inclusion in a future budget request. OOI would provide the basic hardware and infrastructure needed to establish a network of seafloor observatories, with different capabilities, to enable advances in ocean research and exploration.

Communicating via cables across the seafloor is not new, and interrogating sensors on the seafloor and receiving data from them via cables is well-established technology in everyday use. But what is new for the research community is the capability of having continuous power for running sensors and experiments and continuous two-way communication. Fundamental to the proposed OOI is the ability to attach and detach a variety of sensors and instruments to cables on the seafloor without having to pull the cables all the way to the surface. Several NSF-funded feasibility and pilot projects have successfully installed seafloor observatories using newly developed junction boxes and fiber-optic cable protocols. Examples of these and other relevant technology development efforts supported by NSF in recent years, often in conjunction with other agencies, are highlighted below.

A. LEO-15 (Long-term Ecosystem Observatory)

The LEO-15 observatory in 15 meters of water off New Jersey pioneered the seafloor junction box concept. It provided researchers and educators with the capability of two-way communication between shore and seafloor instruments, continuous and ample power to run several instrument packages simultaneously, and a direct internet connection to the observatory. LEO-15 has been providing these capabilities for over five years.

B. Martha's Vineyard Observatory

This observatory on the south coast of Martha's Vineyard has sensor nodes, at depths of about 5 and 15 meters connected to a shore station via a buried cable. The observatory will help provide a better understanding of coastal weather phenomena and will enable scientists to study how winds, waves, currents, seafloor topography and sediment structure, and other factors combine to affect the coastline. In addition, it will provide information about the processes and conditions that affect coastal marine life.

C. H2O (Hawaii-2 Observatory)

In the summer of 1998, a junction box with several scientific instruments was attached to a retired AT&T telecommunications cable midway between Hawaii and California at a depth of about 4,000 meters. A steady stream of seismic, magnetic, ocean current, and temperature data are now being received in real-time from this remote ocean floor location.

D. Moored buoys

Ocean scientists have long used moorings to measure a wide variety of oceanic variables on the sea surface, in the water column and on the seafloor. However, finite battery life and data storage limitations necessitate regular maintenance periods that constrain time and geographic scope of observations. NSF-sponsored research is underway to develop a prototype moored ocean buoy observatory that links junction boxes on the seafloor to moored buoys on the ocean surface. The buoys generate continuous power to the seafloor junction boxes and for transmitting data back to shore via a constellation of Earth-orbiting telecommunications satellites.

E. Hawaii Undersea Geo-Observatory (HUGO)

The Hawaii Undersea Geo-Observatory (HUGO) was established in 1997 as the first submarine volcano observatory. It was emplaced in a relatively benign location adjacent to the seismologically active undersea Loihi seamount, and connected to a shore station via a 40km long fiber optic cable. HUGO monitored earthquakes and eruptions, geology, geophysics, biology, hydrothermal venting and other activities on the underwater seamount until the cable was inadvertently damaged due to chafing against rocks.

F. Bermuda Testbed Mooring (BTM)

The BTM has been deployed since June 1994 and provides the oceanographic community with a deep-water platform for developing, testing, calibrating, and comparing instruments that can obtain long-term data sets. The mooring is located ~80 km southeast of Bermuda. Instruments are being used to collect meteorological and spectral radiometric measurements from a buoy. Subsurface measurements include currents, temperature, conductivity, several inherent and apparent optical properties, and nitrate and trace element concentrations. Data have been sent to shore and to a nearby ship using a new inductive-link telemetry system. The high temporal resolution, long-term data collected from the mooring provide important information concerning episodic and periodic processes ranging in scale from minutes to years.

G. NEPTUNE Plate-Scale Observatory

Through the National Ocean Partnership Program (NOPP), NSF has contributed to a major feasibility study for implementing a lithospheric plate-scale observatory on the Juan de Fuca Plate in the Northeast Pacific. NEPTUNE (North East Pacific Time-series Undersea Networked Experiments) envisions a network of undersea laboratories that would enable unprecedented real-time observations and experiments with changing earth-ocean systems. By laying 3,000 kilometers of fiber-optic/power cable on the seafloor, NEPTUNE would convert the Juan de Fuca tectonic plate and the overlying ocean to a suite of more than 30 extended natural laboratories spaced about 100 kilometers apart. This tectonic plate, one of a dozen or so plates that make up the surface of the earth, is in an ideal location in the northeast Pacific Ocean off the coasts of British Columbia, Washington, and Oregon, and offers a representative spectrum of global earth-ocean processes. The feasibility study and other engineering design studies have shown that establishing a lithospheric plate-scale observatory is ambitious, but doable [5].

Despite the many advances engendered by these and other projects, technical and engineering challenges remain. Primary among these challenges is the need to develop new sensors and sensor systems that are capable of stable long-term operation. Further work and development is also called for on autonomous underwater vehicles that would be “garaged” at certain nodes on the seafloor and deployed either on command, or in response to event detection or conditional sampling.

Based on capabilities of prototypes and design features, observatories would be expected to meet most of the following goals: 1) continuous observations at frequencies from seconds to decades, under all conditions, 2) spatial scales of measurement from millimeters to kilometers, 3) practically unlimited power and broad bandwidth, two-way transmission of data and commands, 4) an ability to operate during storms, 5) an ability to plug in any type of new sensor, including cameras, acoustic imaging systems, and chemical sensors and to operate them over the Internet, 6) bottom-mounted winches cycling instruments up and down in the water, either autonomously or on command, 7) docking stations for a new generation of autonomous underwater vehicles to download data and recharge batteries, 8) an ability to assimilate data into models and make three-dimensional forecasts for the oceanic environment, 9) means for making the data available in real-time to schools and the public over the Internet, and 10) low cost relative to the cost of building and maintaining ships and manned submersible systems.

THE NSF OCEAN OBERVATORIES INITIATIVE

The NSF Division of Ocean Sciences recognizes that the approaches needed to observe and experiment with the physical, chemical, biological and geological processes in our world's oceans have changed over the past two decades. There is increasing emphasis on research involving long-term experiments and sustained time-series observations. This trend requires substantially different infrastructure to enable exciting new scientific discoveries, and continue into the 21st century the rapid rate of scientific progress that began in the early 1960's. More than ten national and international workshops, including a National Academy of Sciences study, have established the intellectual basis and defined the need for new enabling infrastructure.

The Ocean Observatories Initiative (OOI) was developed in response to emerging scientific opportunities and builds upon recent technological advances and successful pilot projects. The OOI would initiate construction of an observatory system to provide the research and education communities with a new mode of access to the ocean. The proposed system has three elements: 1) a lithospheric plate-scale observatory consisting of interconnected sites on the seafloor that span several geological and oceanographic features and processes, 2) several relocatable deep-sea observatories that are based around a system of buoys, and 3) an expanded network of coastal observatories. The primary infrastructure of the OOI is a set of seafloor junction boxes connected to a series of cables running along the seafloor to individual instruments or instrument clusters. The junction box, with undersea connectors, provides a source of power to the instruments, and a means of two-way communications to and from the instruments. Depending upon proximity to shore and other requirements, the junction box is either terminated by a long dedicated fiber-optic cable to shore, or by a shorter cable to a surface buoy that is capable of two-way communication with shore. A data/operations center is also envisioned that would be responsible for insuring unified data handling and dissemination procedures using the most advanced information and communications technologies.

Should funding become available for launching the Ocean Observatories Initiative, a series of Requests For Proposals or Announcements of Opportunity would be issued for its implementation and subsequent operation. The location and types of observatories to be established would be determined through a competitive peer review process.

It is fully anticipated that the observatories enabled by this initiative would be networked together and be an integral part of the proposed Integrated Ocean Observing System (IOOS) that is being developed and coordinated through the auspices of the National Oceanographic Partnership Program (NOPP).

NOPP was established by the US Congress (Public Law 104-201) in Fiscal Year 1997, to facilitate new interactions among federal agencies, academia and industry; in order to increase visibility for ocean issues on the national agenda. NOPP is a collaboration among fourteen Federal agencies to provide leadership and coordination of national oceanographic research and education programs. Through NOPP, the public and private sectors are brought together to support larger, more comprehensive projects, to promote sharing of resources, and to foster community-wide innovative advances in ocean science, technology, and education. To facilitate this coordination mandate, and in response to a Congressional request for “a plan to achieve a truly integrated ocean observing system,” an interagency office to develop a national capability for integrating and sustaining ocean observations and predictions was established. This Ocean.US Office began operation in October 2000 and serves as the national focal point for integrating ocean observing activities. The Ocean.US Office also coordinates ocean observing efforts in the United States with those of other countries.

CONCLUSION

Thirty years ago, NSF leadership helped establish the system of support for the U.S. academic research fleet of modern vessels that is accessible to all investigators. The research vessel fleet enabled, and will continue to enable, the spatial exploration of our oceans. A new system of observatories, accessible to all investigators, would facilitate the 'temporal' exploration of our oceans. As the field of ocean sciences embraces a new paradigm for conducting ocean science research that requires the collection of long time-series data streams needed to understand the dynamics of biological, chemical, geological and physical processes, NSF seeks to provide new opportunities for expanding the underlying enabling infrastructure.

The motivating scientific rationale and justification has been documented, the technical feasibility has been established, and the ocean research community is ready to proceed. Long-term, sustained time-series measurements from a network of ocean observatories will not replace the need for ships and other research platforms, but will be complementary by providing greater spatial and temporal coverage of dynamic processes.

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