Scientific Cabled Observatories for Time Series (SCOTS) Report
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Preface

The National Science Foundation's (NSF) Division of Ocean Sciences (OCE) has entered the new millennium by inviting the oceanographic research community to identify some of the most challenging and exciting new problems of ocean sciences. To this end, a Decadal Committee reviewed several of the most important and promising opportunities for discovery and understanding in the *Ocean Sciences at the New Millennium* report (2001). Many of the areas of high potential for breakthroughs and paradigm shifts involved socially relevant problems. Interdisciplinary approaches were deemed to be attractive for many study topics. The report emphasized the need for new approaches and technologies as the oceans remain poorly sampled because of their vastness, complexity, and diversity of multi-disciplinary processes that often span up to ten orders of magnitudes in time and space scales. NSF developed the Ocean Observatories Initiative (OOI) to "capitalize on new technical capabilities to meet this recent convergence of basic research and societal needs." The Dynamics of Earth and Ocean Systems (DEOS) Steering Committee was formed to provide advice regarding the planning and implementation of the OOI. Based on a DEOS recommendation, NSF formed the Scientific Cabled Observatories for Time Series (SCOTS) committee in May 2002.

The SCOTS committee's primary focus was to elucidate the scientific questions that require, or would most effectively be addressed by, regional networks of multi-disciplinary cabled observatories in three generic domains - the open ocean, geologic plates, and coastal. Cabled systems can, in principle, greatly reduce sampling limitations associated with power and data transmission bandwidth. The SCOTS committee was further charged with reviewing present and future cabled system and sensor capabilities, but only to the extent required to facilitate the scientific discussions that were the primary focus. The *Millennium* report (2001) was used to organize the scientific questions into six topical themes.

The SCOTS Committee first met in Belmont, Maryland on July 16-18, 2002 to develop an outline for the present report and to organize a community workshop that was later convened in Portsmouth, Virginia on August 26-28, 2002. Approximately 50 oceanographers specializing in biology, chemistry, geology, marine meteorology and physical oceanography attended the workshop. They were divided into six science theme working groups and one technology working group. On the first day of the workshop, the science working groups were asked to develop the science questions for cabled observatories in their theme, while the technology group summarized power and communications, sampling platforms, operations and maintenance issues. During the second day, members of the technology working group were reassigned to each of the six science themes as technology facilitators. The composite groups were then asked to define the required sampling infrastructure, discuss implementation strategies, and identify synergies with other working groups. Enabling sensor and system infrastructure is therefore discussed under the specific science themes of this report.

The SCOTS committee placed a very high priority on obtaining community input, using community-wide questionnaires prior to, and attendee questionnaires during, the Portsmouth SCOTS workshop. Copies of the questionnaires and workshop agenda are available on the Consortium for Oceanographic Research and Education (CORE) website (http://www.coreocean.org/SCOTS). Many important issues generic to cabled observatories were articulated and addressed during the workshop. Several novel uses of cabled systems and synergistic aspects of observing systems emerged. These are summarized as part of this report in the spirit of consensus building by the oceanographic community. Finally, this report was reviewed by six scientists selected by NSF while comments were again solicited from the community at-large.

The SCOTS report's primary audience is intended to be the National Research Council (NRC) Committee on Seafloor Observatories. The intent of the NRC study is to develop an implementation plan to establish a network of seafloor-based observatories to support multidisciplinary research. While this report focuses on the science problems best served by cabled observatories, the NRC study will describe the strategies needed to carry out the priority science. In addition, the SCOTS report is expected to be one of several community resources for scientists and engineers already working with, or developing new plans for, cabled observatories.

Acknowledgements

The SCOTS report reflects what will be a year-long community effort. The SCOTS committee is to be commended for their enthusiasm and hard work for the full duration of this project. Lead authors of the various sections are indicated in the Appendix. The committee and workshop attendees generously shared their ideas and opinions in a most collegial spirit. The six anonymous reviewers are thanked for the key role they played, providing excellent suggestions on overall organization, points for clarification, and specific comments, several of which have been incorporated directly into the text. Responses obtained by distribution of the draft report through a public website are also appreciated. Every comment received was read and considered.

Throughout the process, discussions with Alex Isern and Larry Clark were numerous and most valuable. Their efforts are greatly appreciated. The work of the committee was facilitated by the extraordinary efforts of Bill Fornes and Shelby Walker. We thank Emmeline Romana for her assistance with the preparation of this report.

Tommy Dickey and Scott Glenn

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Executive Summary

The Scientific Cabled Observatories for Time Series (SCOTS) Committee was initiated by the National Science Foundation (NSF) in April 2002. The SCOTS Committee was asked to provide input for the NSF Ocean Observation Initiative (OOI) by exploring new science topics that could be most effectively addressed using the advantages afforded by regional cabled observatory technologies and approaches. The Committee also reviewed the status of cabled observatory and related technologies in order to provide context for the activity. Extensive efforts were made to capitalize on the oceanographic community's expertise by forming a steering committee, soliciting community-wide input through widely distributed questionnaires, and facilitating open discussions through a workshop held in Portsmouth, Virginia. The report was critically reviewed by individuals selected by NSF, and comments were requested from the community-at-large.

Below, we summarize some of the general results of the SCOTS activities.

1. ***Cabled Observatory Science:*** Scientists attending the workshop identified important scientific questions within six longstanding scientific themes that could be addressed because of several attributes of cabled observatories. In particular, the capability of cabled observatories to supply power sufficient for energy demanding sensors and systems, to sample at high data rates for long periods, to collect a large number of virtually continuous and diverse measurements over different spatial scales for unprecedented interdisciplinary coherence analyses, and to communicate the full datasets to shore in real-time time enables new classes of scientific questions to be addressed. The bulk of this report is devoted to the demonstration of this assertion through specific examples of relevant scientific problems and several types of requisite technologies. It is noted that some of the science questions would be appropriate for, and benefit from, shorter duration pilot studies for cabled observatories using technologies that could be relocated as part of a phased implementation.
2. ***Scientific Synergies:*** The report describes several types of scientific problems, potential breakthroughs, and paradigm shifts that require or can be most effectively addressed using cabled observatories. Interestingly, the independent workshop subgroups found that specific experiments would often be improved or optimized by concurrent complementary experiments recommended by other subgroups. Thus, many potential synergies were identified. For these synergies to develop, careful matching of both time, and the more difficult spatial, sampling scales is required.
3. ***Implementation:*** Six topical science themes (summarized below) addressed in this report collectively encompassed the three OOI geographic domains: coastal, open ocean, and plate-scale. Discussions focused on generic settings, rather than specific geographic locations, for addressing the science problems. Some of the science themes could be adequately conducted within a single domain while others would require simultaneous time series in two or all three of the domains. Science themes involved processes spanning nearly ten orders of magnitude in time and space (e.g., turbulence and episodic events to decadal oscillations and global climate change). Thus, a multi-platform approach and well-conceived nesting of assets along with the utilization of admittedly model-dependent Observing System Simulation Experiments (OSSEs) were seen as important observational strategies. Scientists are cautioned against an

overly-optimistic view of still evolving capabilities. Some significant science questions could be at least partially addressed during phased 3-5 year duration technology pilot studies, after which portions of the technology could even be relocated if desired.

4. ***Both New and Used Cables:*** It was determined that cabled observatories could be developed through initiation of completely new cabled systems and by taking advantage of abandoned cables that would be donated by the commercial sector. Both models have already proven successful and could be pursued for specific scientific problems and applications.
5. ***Scientist-Defined Sensor Needs:*** Scientific working groups were asked to suggest sensors, sampling strategies, array designs, and possible locations for science problems relevant to the cabled approach. A common theme that emerged from participants and reviewers alike was that sensors and systems are as important as cables and platforms. Many of the measurements required under the science sections cannot be made today. There is a real need for accelerated development of remote oceanographic sensor and sampling systems, interfacing standards, anti-fouling strategies, and autonomous platforms for sensor deployment and the retrieval of collected sediment, water and biological samples. It is critical to achieve the appropriate mechanisms, balance and timing in the provision of continued funding for cabled infrastructure that includes the necessary sensor systems. An important application of cabled observatories would be the testing and improvement of new durable sensors and sensor protection systems. The need to develop new ways to maintain sensors and sensor calibrations for extended periods in a harsh environment was given high priority.
6. ***Modeling:*** Modeling was viewed as an important if not essential component of most cabled observatory plans. Intensive measurement programs could be directed to gain a better understanding of processes and parameterizations within numerical models, providing valuable or essential data for model development and testing, parameter estimation, and formulation of new empirical relations for several of the problems discussed in the report. Numerical models would enable the collation of distributed observations on requisite time and space scales. Combining the time series data with other spatial data sets obtained from a cabled observatory and assimilating these into numerical models would provide improved analyses and predictions of phenomena (presently largely unobserved) for scientific advances, adaptive sampling, and for operational stakeholders.
7. ***Public Outreach:*** The focus of the Committee was on scientific aspects; however, it was also evident that the additional opportunities afforded by cabled observatories could be readily utilized for engaging the public and for educational outreach activities (e.g., reporting of events and discoveries such as submarine volcanoes, red tides, hurricane passages in real-time to aquaria, museums, educational institutions ranging from kindergarten to graduate schools).

Brief summaries of the results of the six science theme and technology sections follow. The science questions concentrate on those within each theme that can be best addressed with cabled seafloor observatories:

1. *Earth Structure and Dynamics of the Ocean Lithosphere:*

Science Questions: Science questions focused on three subcategories. Deep earth questions dealt with the structure of the earth's core, core/mantle boundary, and mantle convection. Regional geo-dynamics and neo-tectonics considered variability of stresses and deformations across plate boundaries, and variability of seismic activity. Local volcanic processes addressed the nature, extent and variability of submarine vulcanism.

Why Cabled Observatories?: Deep earth imaging requires more paths to remote deep-ocean locations for high data-rate seismics over extended periods. Neo-tectonics requires long-term seismic arrays located near plate boundaries to detect small earthquakes and on both sides of the boundaries to eliminate biases. Submarine volcanism is best monitored with long-term seismic arrays around active hot spots.

Implementation Strategies: Remote open ocean observatories are economically viable through cable re-use programs. Coverage in polar regions is especially sparse, with the Pacific-Antarctic Ridge, the Mid-Atlantic Ridge, and the Northeast Pacific south of the Aleutian Islands listed as priorities. Plate boundaries could be sampled with sparse regional seismic arrays that are locally enhanced with mobile arrays in locations demonstrating increased activity. The Juan de Fuca plate is the smallest of the still intact plates along the U.S. northwest coast. Submarine volcanic observatories will be smaller in areal extent, and likely serviceable with a single main cable from shore which spiders into an array of science nodes. Active volcanoes near U.S. shores (e.g., Axial, Loihi) are more likely to exhibit predictable volcanic activity than spreading centers.

2. *Fluids and Life in the Ocean Crust:*

Science Questions: Specific environments for cabled scientific studies included ridge/hydrothermal systems, continental margins and coastal zones. Cross-cutting questions included: What drives change in the subsurface biosphere? Does sub-seafloor biology affect pore fluid chemistry, circulation, or fluxes? What is the rate of biomass production by chemosynthetic processes?

Why Cabled Observatories?: Science questions require long-term and reliable environmental and seismological time series and responsive event sampling. The goal is to track and cross-correlate changes in sub-seafloor, seafloor and water column processes on time scales of seconds to decades.

Implementation Strategies: The suggested approach is to concentrate on a small number of geographically diverse sites. Areas that would especially benefit from a cabled observatory program include mid-ocean ridges, hydrothermal vents, continental margins, and coastal zones. Multiple locations with a single cable that spiders out to science nodes is likely sufficient.

3. *Coastal Ocean Processes:*

Science Questions: Cross-cutting science issues for integrated coastal observatories included synoptic-scale interactions between the coastal ocean and the atmosphere or deep ocean, and the impact of river-supplied buoyancy, nutrients, sediments and toxins on physics, chemistry, biology and geology of the coastal ocean. The cabled observatory component of an integrated coastal observatory would focus on questions concerning water column mixing and vertical fluxes, benthic processes, air-sea interaction, decadal effects of climate change, across-shelf fluxes and flux gradients, dynamics of plumes, and wave-current dynamics in heterogeneous environments.

Why Cabled Observatories?: Multiple co-located sensors for turbulence, nutrients, suspended sediment, and optical and acoustic imagery require high power and large data-rates. Real-time communications ensure that data will be recovered up until the time systems fail, are damaged, or are lost due to severe conditions.

Implementation Strategies: Cabled observatories should be integrated into the more extensive national coastal ocean observing program at a range of sites on the Atlantic, Pacific and Gulf coasts. A phased implementation plan is recommended, specifically, integrating existing observatories, using existing shore landings to extend cables cross-shore from the coast to the shelf break, use shallow science nodes as testbeds for deep nodes, and finally, add nodes and cables to progressively expand the network based on experience.

4. *Turbulent Mixing and Biophysical Interactions*

Science Questions: Questions within three topical areas (phytoplankton community structure, the formation, dissolution and export of marine snow, and benthic community structure) were emphasized for the coastal zone, but could be extended to deep sites. All would benefit from new datasets to improve basic turbulence modeling. Specific questions include: How is phytoplankton community structure influenced by the interaction of turbulent motion, stratification, light fields and nutrient supplies? How is marine snow affected by upper-ocean turbulence? How does the turbulent bottom boundary layer structure influence benthic communities?

Why Cabled Observatories?: High power and data rates are required for dissipation-scale microsensors, multifrequency acoustics, and video/still photography. An extended time presence is required for cross-correlation analysis of multiple realizations to develop relations between physical observations and biological response. Experience at cabled sites can be translated to non-cabled sites to improve statistics.

Implementation Strategies: Spatial aliasing is an inherent problem with the intensive time series measurements required for turbulence studies. The largest spatial gradients are in the vertical, so vertical sampling capabilities are key. This is followed by the need to have sufficient horizontal spatial resolution to separate advective changes from true temporal changes. A primary profiling node with spidering secondary profiling nodes is recommended. Most of the science questions focused on coastal issues, but these could be adapted to deeper water.

5. *Ecosystem Dynamics*

Science Questions: Science questions were developed into three themes based on region, plus one overarching theme. The pelagic response to upper ocean variation was emphasized for the deep basin. The benthic or bentho-pelagic response to upper ocean variation was also considered for the deep-sea adjacent to a productive shelf. The benthic and pelagic response to seafloor hydrothermal activity was discussed for both deep hydrothermal vents and marginal cold-seeps. Lastly, studies of human interactions with the seafloor communities, both observational and manipulative, were discussed.

Why Cabled Observatories?: The many different species to be studied within this topic require a wide variety of sampling techniques, including video, acoustics, and water/particle sampling. The multiple co-located sensors require high power, high bandwidth and flexible sampling. Long-term continuous time series at multiple sites along lines running across the coast and into the deep sea fit well into typical cabled topologies.

Implementation Strategies: A variety of habitats spanning coastal to deepwater are required. Continental shelf sites are desired because they are highly productive, have high rates of nutrient cycling, and contain the majority of commercially important species. Deep-sea sites are desired because historically they have been less accessible, and therefore are likely sites for new discoveries. Deep-sea sites of interest include sites underlying a dynamic frontal region, sites in close proximity to a productive shelf, sites near deep hydrothermal systems, and sites near marginal cold seeps. A phased implementation is recommended for multiple regional observatories, starting with the extension of existing systems to initiate observations.

6. *Ocean, Climate, and Biogeochemical Cycling*

Science Questions: Science questions first considered the description, understanding and prediction of the impact of climate change and variability on smaller-scale regional processes. This is followed by the need to quantify the role of regional carbon cycling in the global carbon budget. Lastly is the need to better understand the effect of episodic events within long time series on biogeochemical cycling.

Why Cabled Observatories?: High power and bandwidth are required for high-frequency sampling of high spectral resolution optics, video, multi-wavelength acoustics, and AUVs necessary for long-term spatial measurements in both the coastal and open ocean. A phased implementation plan, possibly aided by OSSEs, is recommended to determine the proper spatial scales and sampling locations. The new datasets also are required to improve the process models, leading to improved subgrid-scale parameterizations for large-scale numerical models.

Implementation Strategies: Cabled observatory time series should be integrated with other spatial sampling systems (including other elements of this OOI) to acquire regional observations spanning the coastal to open ocean domains. The cabled scientific nodes must include adaptive mobile sampling platforms to locally resolve the relevant horizontal spatial scales. A recommended phased implementation plan is to first enhance existing systems as testbeds, to deploy regional coastal observatories that can be linked into a national network, to extend these to nearby deepwater sites, and finally to extend to remote open ocean sites in adverse environments.

7. Technology to Support Regional Scale Cabled Observatories

Current in-place and funded scientific cabled observatories in the United States include short cable runs (less than 100 km) to both coastal and deep ocean sites, and long cable runs reusing retired telecommunications cables. Regional-scale cabled observatories may be several thousand kilometers in length, may have a looped topology offshore with a multiple shore landings, and may have a maximum science node spacing of 80-100 km dictated by the fiber optic repeaters. A typical observatory is expected to distribute 100 kW of shore-power, providing about 10 kW of power to individual subsea scientific nodes. Presently available Gigabit Ethernet is expected to expand to 10 Gigabit Ethernet by the time regional cabled observatories are ready for deployment. AUVs, both propeller-driven with docking ports and long-duration glider-type, are viewed as complimentary technologies that will enhance the scientific effectiveness of regional cabled observatories. Maintenance of the envisioned systems will require significant ship, ROV and diver support. Governance issues remain paramount, with the need for scientific oversight a key issue.

Recommendations

1. ***Community Participation:*** The SCOTS Committee, NSF and CORE made every effort to engage the community in this process. Workshop attendees overwhelmingly felt that the meeting accomplished its goal of obtaining input from the scientific community on those questions best addressed by the cabled approach. Continued public comment on the results of this workshop, including comment from the international community, is encouraged.
2. ***Workshop Consensus:*** The workshop consensus was that NSF should be encouraged to support the development of regional cabled observatories in all three domains - open ocean, geologic plates and coastal. The science questions developed through numerous SCOTS activities and documented in the six science theme sections of this report support this important point. Regional open ocean observatories are recommended by the lithosphere (for deep earth imaging and volcanic processes), fluids and life, and ecosystem working groups. Regional plate-scale observatories were recommended by the same three working groups, with the Juan de Fuca plate noted as the closest small (but still intact) plate to the U.S. coast. Five of the six science themes (all but lithosphere) recommended the development of regional coastal observatories.
3. ***Retired Telecommunications Cables:*** There was widespread support for relocating retired telecommunications cables to remote areas to complete the deep Earth imaging array. While this may be one of the primary considerations for determining the new locations, once in place, the cable could support a much wider variety of sensors and systems to facilitate ocean studies also desired by the fluids and life and the ecosystem working group. It is recommended that current and future funding mechanisms be used to ensure that retired cables deemed to be scientifically useful are adopted for community use in a timely manner.
4. ***Combined Use for Coastal & Deepwater:*** Scientific working groups that developed coastal questions assumed that they would be able to tap into cables running across the shelf and into deep water to obtain power and communications for multiple scientific nodes on the continental shelf. Multiple working groups even suggested that coastal questions could best be addressed with several cross-shore cable runs into deepwater. The potential for conflicts over power and bandwidth between deepwater and coastal experiments, as well as the potentially higher risks for cables on the continental shelf, were noted. The development of technical solutions, possibly multiple cables to avoid potential conflicts and provide redundancy, was encouraged by all working groups.
5. ***Science Platforms:*** A variety of platform-based developmental activities for technologies, infrastructure and integration were deemed essential or highly recommended. These include testing of cable runs over 100 km with looped cable topologies, development of robust profilers, definition of standard sensor suites for scientific nodes, development of docking stations and navigation for autonomous underwater vehicles, integration of bottom tripods, moorings, AUVs and gliders within the regional networks, and continuing progress in acoustic and electro-optic laser communication systems.
6. ***Sensor and Systems:*** It is expected that the scientific nodes will include facilities to install a suite of standard sensors, project specific sensors, and new experimental sensors. It is recommended that actions be taken to establish standards for instrument interfacing, data distribution systems, and management policies. Virtually all planning

discussions indicated that many critical variables simply cannot be measured *in situ* at present. It is recommended that new means be considered for accelerating development of new sensors and systems, particularly for biology, chemistry, optics, and acoustics.

7. ***Phased Implementation*:** Phased implementation plans that included the immediate collection of initial datasets were, as expected, popular with scientists. Nevertheless, this is supported by their strong belief that the development of new sensors and sampling systems was equally important to the success of cabled observatories as new cables, higher power transmission, high speed data communications, and undersea junction boxes. Implementations that include immediate data collection allow the development tasks to proceed in parallel.
8. ***Installation/Maintenance ROVs:*** It was not evident from workshop discussions that sufficient numbers of ROVs are presently available to install and maintain a regional cabled observatory. Required ROV capabilities need to be better defined, and the availability of ROVs with sufficient capabilities should be assessed.
9. ***Complementary Observation Systems:*** The need for a diversified portfolio of observing capabilities is widely supported by the oceanographic community. Cabled observatories should make a significant contribution to meeting that need. It is recognized that the cabled observatory approach is clearly not the most practical or economical approach for every important scientific problem and cannot supplant observations from satellites, moorings, drifters, AUVs, and gliders. Thus, efforts to integrate future cabled observatories with other observational programs are essential to maximize the scientific products and ensure satisfaction of an even larger set of scientific goals.

8\. ***Modeling:*** The development of cabled observatory systems needs to include modeling components to help optimize the numbers and types of observatory platforms, their placement, their sensor payloads, and their sampling regimens. In combination with other observing systems, modeling will be a vital tool to facilitate data integration and synthesis as well as to advance predictive capabilities. Scientists are cautioned that model-based data assimilation as a mechanism to connect science objectives with observatory measurements will require greater involvement of the modeling community to set realistic expectations.

10. ***Scientific Synergies:*** The identification of potential synergies between the six science themes was a significant outcome of this workshop. While these synergies recognized the importance of long-term continuous time series measurements, the ultimate success of these synergistic efforts is just as critically dependent on what spatial arrays are needed to answer the different questions. For example, is the seismic scale array also the best to answer carbon flux questions? For synergy to happen, the required spatial scales still need to be identified and matched.
11. ***Data Management:*** This report does not deal with data management issues, as they are beyond the committee's expertise and charge. Nevertheless, it is widely recognized that data management is critical to the success of all ocean observing efforts. It is anticipated that data management issues will be addressed by future committees, and that the data management issues for cabled observatories will greatly benefit from ongoing discussions occurring in other observatory programs such as the International Ocean Observing System (IOOS).
12. ***Funding:*** A major concern of the scientific community was the level of funding required for regional cabled observatories. The committee recommends that a well-

conceived balance between infrastructure and experimental assets be established in the planning of the expenditure of MREFC funds. Recognizing the potential impacts to existing science budgets for both the maintenance and scientific research associated with cabled systems, the Committee recommends that NSF address these questions in order to help build community support. Specific concerns were raised on the potential impact on the academic fleet, not only on operations schedules, but also on the need for differently outfitted vessels.

13. ***Governance:*** Program management and leadership are key issues which still need to be worked out. Success will depend on leaders with a combination of scientific and organizational skills. Control of cabled observatory operations including the setting of priorities for science missions needs to be addressed. Importantly, it is the strong consensus of the scientific community that participation and oversight by scientists is essential to nurture and inspire an active long-term research-driven cabled observatory program.
14. ***Education:*** It was noted that past successes in observatory efforts most often come from the people involved, not the technology. It is recognized that there are insufficient numbers of people available in the oceanographic community with the necessary skills to operate all the ocean observatories envisioned. It will be necessary to continue to entrain and educate skilled people for these efforts to succeed. This includes expanding K-12 outreach programs, and, while still maintaining Ph.D level programs, evolving a new emphasis on Bachelors and Masters level education in oceanography.

Background

Sustained ocean observing systems hold the promise of revolutionizing ocean related science within this decade. Enabled by technological advances and further fueled by societal need, a wide range of ocean and earth observing systems are being planned, proposed, deployed and operated. Both envisioned and existing observation systems emphasize real-time datasets for event response and adaptive sampling, well-sampled spatial and temporal contexts for limited-duration or process-study experiments, and sustained operation to observe long-term trends and capture rare episodic events. Collaborative science is similarly emphasized, with the widespread availability of increasingly multi-disciplinary datasets stimulating previously unfeasible cross-correlation analyses in the search for new associations or causal relationships. Extensive observations are increasingly being used in combination with interdisciplinary models through growing model development, coupling, validation and assimilation activities. The rapidly expanding observation and modeling capabilities are enabling scientists to consider an entirely new set of interdisciplinary science questions. In turn, the new questions can be used to guide and prioritize implementation strategies for upgrading existing, and deploying new, observatories.

The Scientific Cabled Observatories for Time Series (SCOTS) report is a significant part of the implementation process for one specific type of ocean observatory. It documents community input on the scientific questions best served by regional networks of the cabled observatories in three targeted domains - the open ocean, geologic plates, and coastal. The report is directed primarily toward those charged with the development of observatory implementation plans that address the priority science identified here. We also expect that it will be a valuable resource for scientists interested in developing cabled observatory research programs.

Aim and objectives of this report

The SCOTS report focuses on several representative interdisciplinary science problems that will likely require, or can benefit from, emerging technologies and advanced oceanographic infrastructure. Starting with four disciplinary *Futures Reports*, the NSF Decadal Committee report (*Ocean Sciences at the New Millennium*) identified six cross-cutting science themes that provided the most important and promising opportunities for discovery and new understanding over the next decade. Adding their support to these six science themes, the National Research Council Committee on Seafloor Observatories report (*Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*) identified major science problems under each theme for which geographically distributed long-term time-series observations would be either very useful or useful. Their report defines seafloor observatories as both cable-based and moored-buoy/seafloor junction box systems, and discusses the technical requirements for these systems to support observatory science. These six themes were again adopted by the SCOTS Steering Committee with the goal of identifying the science questions under each topic that could be best addressed specifically by multi-disciplinary regional cabled observatory networks. Following the topics enumerated by the Committee on Seafloor Observatories, the six themes are restated here as:

- Dynamics of the Earth Structure and Ocean Lithosphere
- Fluids and Life in the Ocean Crust
- Coastal Ocean Processes
- Turbulent Mixing and Biophysical Interactions
- Ecosystems Dynamics
- Ocean, Climate, and Biogeochemical Cycling

The science questions described here take into account previous planning documents and input from the scientific community at the SCOTS Portsmouth Workshop (August 26-28, 2002). This report also briefly reviews the present status of cabled observatory technology, and identifies possible strategies to carry out dedicated scientific studies, such as those listed above, via cabled observatories. This includes design considerations for enabling technologies and their present and future capabilities. An overriding theme involves optimal utilization of cabled observatories for a multiplicity of research activities and interdisciplinary synergies.

As programmatic background, the National Science Foundation (NSF) Division of Ocean Sciences (OCE) has established an Ocean Observatories Initiative (OOI) to facilitate the temporal and spatial exploration of the ocean. The SCOTS report documents one more step in an ongoing series of NSF-sponsored planning activities that are now being used to support the OOI. With proposed support from NSF's Major Research Equipment and Facilities Construction (MREFC) account, OCE plans to construct an integrated observatory network that will provide the oceanographic research and education communities with a new mode of access to the ocean. The OOI has three elements: 1) regional cabled observatories on the seafloor spanning multiple geological and oceanographic features and processes, 2) globally distributed moorings that could be deployed in harsh environments such as the Southern Ocean, and 3) new construction or enhancements to existing facilities leading to an expanded national network of coastal observatories.

Previous reports (see reference list) have discussed the importance of observatories for advancing multi-disciplinary ocean research, describing the overarching scientific themes that require regional time-series data sets as well as the types of observatories needed to acquire these data. NSF has used this advice to develop the OOI. As part of the OOI, three generic types of sampling domains are targeted for regional cabled observatories: open ocean, geologic plates, and coastal. To further the planning for this initiative, community input is required to define the scientific problems that require or would most effectively be addressed by regional cabled observatories. For this specific purpose, NSF, under the direction of the DEOS Steering Committee, formed the Scientific Cabled Observatory for Time Series (SCOTS) Committee. The findings of the SCOTS Committee are reported here.

What is a cabled observatory?

A cabled observatory is defined operationally here as an unmanned system located in a fixed region that uses electrical/fiber optic cables either laid on or buried just below the seafloor to provide substantial electrical power and real-time two-way communication links between a shore base and often multiple measurement platforms deployed offshore. The observational assets supported by the cable system will generally include a variety of stationary and mobile platforms enabling coherent interdisciplinary measurements over time and space (3-dimensional) scales sufficient to study a broad suite of processes in regions selected on the basis of scientific problems such as those outlined below. Figure 1 illustrates three conceptual regional cabled observatories deployed within a generic region that includes a spreading zone, a seamount, a subduction zone and a continental shelf. Short cables (less than 100 km) can run across the shelf from multiple locations to a small number of scientific observation nodes located within both coastal and deepwater sites. Communication between the different scientific sites is accomplished via standard land lines. Retired telecommunication cables, either operated in-place or moved to a new desired location, can be equipped with scientific nodes as a cost effective alternative for long cable runs to remote sites. Regional-scale, possibly-looped, cables with multiple subsea measurement sites supported by a few shore landings is the third concept. The regional concept, illustrated here for a deepwater domain, can also be applied to a coastal or plate-scale domain.

For the scientific observation nodes, a variety of offshore measurement platforms have been developed or proposed, including (a) bottom-fixed sensor packages for local point or profiling acoustic measurements, (b) bottom tripods, surface-piercing towers, winched, buoyancy controlled, or wire-crawling profilers, and subsurface/surface moorings for vertical extent in the water column, (c) devices for deployment within bore holes for vertical extent below the seafloor, and (d) autonomous underwater vehicle (AUV) docking ports and acoustic communication and navigation networks for enhancing spatial sampling. The platforms generally provide interfaces for sensors relaying data to shore and receiving new sampling commands and timing signals.

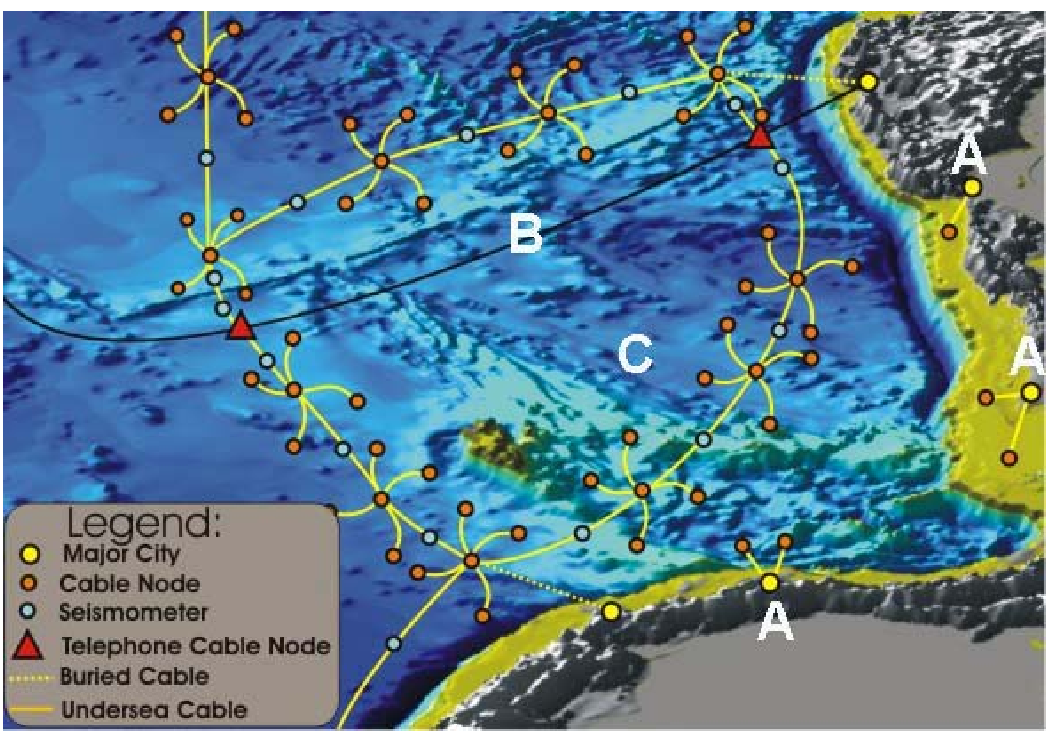


Figure 1: Illustration of three cabled observatory concepts, including (A) multiple short cables running to both deep and shallow water sites, (B) reused telecommunication cables for long runs to remote sites, and (C) offshore looped cables with multiple measurement sites.

What are the unique advantages of cabled observatories?

Cabled observatories have unique advantages for collecting long-term time series data that usually fall into the categories of either sustained high power delivery or real-time high bandwidth communications. A cabled observatory network could provide enhanced regional coverage of a portion of the seafloor, providing multi-disciplinary time series data in a scientifically significant three-dimensional space.

Sustained high power delivery. Cabled systems are anticipated to be capable of delivering high power to offshore sites for sustained periods, enabling scientists to use sensors and sampling systems more effectively than with battery operated platforms. Instruments with high power requirements are rarely deployed for long-periods of continuous sampling or in combination with other high power consuming sensors. Trickle-charged batteries will still be required where very high power is needed for short periods of time, such as for lighting and AUV recharging. Prototype instruments may have high power requirements initially, and after the technology is proven to be scientifically useful, can then be miniaturized for lower power consumption. Removing batteries from observation platforms leaves more physical space for multiple sensors, promoting comparisons of similar sensors and clustering of different sensors for specific disciplinary measurements. Instrument clustering promotes cross-correlation and coherence and phase analyses that may not have been anticipated or affordable in the past.

Real-time high bandwidth communications. Cabled observatories are expected to provide high-bandwidth two-way communications that could include video, hyperspectral optics and broadband acoustics. This capability will promote high frequency sampling for extended time periods by transferring datasets to shore rather than storing these data at sea on instrument packages. Immediate on-shore data storage enables the complete dataset rather than a subset to be available in real-time for on-shore processing. If an instrument is lost or damaged during a severe event (storm, volcanic eruption, etc.), all data stored onshore up to that point are saved even if the instrument itself fails or is lost. The communication network also enables the distribution of precision time calibrations and synchronizations throughout the system, enabling the system to work as a coordinated network.

The availability of power and communications does not guarantee that long-term scientific-quality datasets will be acquired. Long-term deployments are also constrained by the harsh environment, where biofouling, corrosion, filter fouling, etc. can limit some sensors' ability to hold their calibrations or otherwise return useful data for extended periods. Combining sustained delivery of power from shore with an on-shore data storage capability only means that the subsurface instrument cycling times are driven by sensor calibration and performance requirements rather than battery power or data storage limitations. This has led to ongoing and proposed efforts to extend the time periods that sensors can collect scientifically useful information. Examples include antibiofouling copper shutters for optical sensors, enclosures for storing sensors between measurements, or systems with multiple identical sensors in which some are active and others are held in reserve in protective casings as replacement spares for later use. Power availability makes many of these life-extending systems possible, and real-time two-way communication optimizes their use for long-term interactive deployments.

What are the attractive features of cabled observatories?

The unique advantages of cabled observatories translate into several attractive science-enabling features. Some of these features may be duplicated by other technologies, but are equally feasible or potentially easier to implement with cabled systems. Some of these include:

(1) Observatories promote the sustained and continuous collection of a standard suite of parameters that are available to other researchers, either as datasets of opportunity for specific events, or as background datasets that the scientist would not have collected as part of a short-term, highly-focused research project.
(2) Instrument deployments limited only by sensor calibration and performance lifetimes can be used to promote the collection of continuous scientific-quality measurements for long periods. Long-term datasets can be used in climate studies, to place short duration process studies in a long-term context, to provide multiple realizations of common events for statistical cross-correlation analyses, and to capture rare episodic events.
(3) Sensors can be monitored and adjusted in real time. Damage to sensors or sensor failures can be detected so that appropriate corrective actions can be taken. Actions could include changing gains, activating spare sensors, changing cleaning cycles, or scheduling replacement. Sampling can be adjusted from shore, either by automatic triggers or human intervention, based not only on event detection by local systems, but also on information available from the entire network or other external sources.
(4) Real-time data transfers to shore can provide inputs to product generation and visualization software. Real-time products can be used for adaptive sampling guidance, forecast model assimilation (usually in combination with other spatially distributed datasets), and public outreach and environmental management activities with societal impacts.
(5) Rugged bottom platforms have provided for sustained operations during extreme surface events like storms. Independence of the weather allows sampling to continue during time periods when no ship would put to sea, or if it did, little would be accomplished. Platforms similarly will need to be designed to survive extreme bottom events like submarine turbidity flows, tectonic events at ridges and volcanoes, or intrusions by bottom trawlers.
(6) Precision 3-dimensional navigation networks for autonomous underwater vehicles and bottom rovers can be installed and maintained for sustained periods.
(7) Cabled observatories will promote the establishment of standardized test facilities, both onshore and underwater, that can be readily available for new platform and sensor development.
(8) A network of seafloor cabled observatories can contribute to and benefit from a larger network of real-time observatories and systems that includes satellites, radars, buoys, autonomous vehicles and drifters.
(9) All real-time observatories, cabled or otherwise, provide tremendous opportunities for public outreach and education at all levels.

Synergistic use of cabled observatories

This report populates the six themes discussed above with science questions formulated through SCOTS activities that are best served by or only possible with cabled observatories. Individually, some of these themes may make stronger arguments for cabled observatories than others. However, if even one of the themes is deemed strong enough to justify the investment, the observatory then becomes a platform of opportunity that can potentially be used for the benefit of all the themes. Every node or plug can enable a unique experiment that is independent of the others, but benefiting from the common infrastructure and datasets. It is expected that most cabled systems will be used for a variety of multi- and interdisciplinary studies. Even questions addressable with other emerging technologies may be reconsidered by scientists for cable-based studies if the infrastructure is already in place and access is simple.

Numerous battery-operated internally-recording seafloor-based observation systems are already used to study diverse scientific processes in the water column, at the water/seafloor interface, and below the seafloor. The power and communication infrastructure provided by seafloor cabled observatories promotes the clustering of instruments from multiple disciplines in the same location. Datasets from the different co-located instruments will prove complementary in ways unanticipated by investigators. Instrument clustering can save money, since common basic background measurements needed by many scientists will already be available, either as part of another scientist's instrument package, or as a basic sensor suite maintained by the cable operators. Instrument clustering also can save on sensor maintenance costs, since the same ships, remotely operated vehicles (ROVs) or divers can be used to service multiple sensors on the same cruise. Maintenance vessels and ROVs could be instrumented, providing additional water column and atmospheric data at regular scheduled and emergency maintenance intervals.

Cabled observatories will require the development of an extensive data-handling infrastructure. The OOI assumes that a phased approach to the deployment of cabled observatories will allow sufficient time for the parallel development of the required Ocean Information Technology Infrastructure (OITI). This infrastructure is intended to support community modeling, data assimilation, data archiving, analyses, and visualizations.

Cabled observatories will form the seafloor-based component of a larger ocean observation network that includes satellites, aircraft, shore-based radars, moorings, towers, drifters, profiling floats, gliders, ships, submarines, ROVS and AUVs. Many of these systems will be able to take advantage of the OITI development discussed above. Sensor development for cabled systems, especially for long-duration deployments, also feeds back into the entire network. The availability of real-time data from the network may increase the need for, and the effectiveness of, mobile platforms like aircraft, ships, submarines, gliders and AUVs that can be directed to specified locations at given times to intensively sample particular processes.

Report organization

An executive summary and a list of recommendations are found at the beginning of this report. This is followed by the supporting documentation that includes this background section, the six science themes, and the technology theme. Within the science themes, focus is placed on those aspects that are best addressed with cabled observatories. Each section includes a science-box that provides a concrete example of how cabled observatories can benefit science questions developed within that theme. A technology section outlines some of the important considerations for accomplishing the scientific goals of the individual science sections, and includes a technology box on program management. Closing remarks include: (a) other applications of cabled observatories that were recognized, but not fully described because of the scope of the present report, (b) technical challenges and other issues, and (c) relationships with other observational programs. The appendices include lists of steering committee members and participants, and the answers to Frequently Asked Questions that were raised in the process of preparing this report.

WORKING GROUP RESULTS - SCIENCE THEMES AND TECHNOLOGICAL NEEDS

1. Earth Structure and Dynamics of the Ocean Lithosphere

Introduction

Cabled observatories in the ocean can provide the power, bandwidth, flexibility, real-time data and response capabilities necessary for detailed studies of the processes that continue to transform the earth. While there are now hundreds of seismic and/or other geophysical observatories around the planet, all but a few are located on land, and only two of those in the ocean provide scientists with real-time data; thus, more than 60% of the earth is poorly observed. As nearly all of the tectonic plate boundaries are in or bordering the oceans, available data are heavily biased by observations from the landward side, or by observations from distances often greater than 1,000 km.

The coincidence of the maturation of several technologies with recent discoveries in the oceans promises a high return for investment in cabled observatories in the ocean. As recently as 40 years ago we had no idea that there even were plates, let alone that the spreading centers account for more than 80% of volcanism in the world, generating a large fraction of its mineral resources and an environment capable of sustaining life without external energy.

Applications of tomographic methods to earthquake seismic data have resulted in several models for the structure of the earth's interior that are now converging to a clear picture. Many parts of the interior, however, are poorly resolved by the scarcity of signals passing through them. This lack of data results from earthquakes commonly occurring only in particular regions combined with the siting of almost all seismic stations on land. Installation of a distributed network of ocean floor observatories, both cabled and autonomous buoy-based, in regions far from land (including beneath polar ice) would go far towards filling in these gaps in our knowledge.

Plates behave and deform rigidly in the plate tectonics model, but evidence suggests that the model breaks down in many situations, and that plates can deform significantly in response to stresses at their boundaries. The extent of this deformation and the mechanisms and time scales involved are important parameters in understanding earthquake activity. Our ability to measure these stresses and deformations and how they propagate across plates are severely limited in the oceans, and would be greatly enhanced by measurements from seafloor observatories.

Earthquakes and volcanic activity at the plate margins constitute a significant hazard to large populations, particularly in coastal regions. While actual prediction of earthquakes may not be possible for the foreseeable future, a more basic understanding of the processes that lead to earthquakes and volcanism is required to adequately quantify the hazards involved. In some heavily populated places in the world, we have only a vague idea of when or even whether to expect large earthquakes. A critical element to improve this situation is monitoring of potential trouble spots for decades or even centuries to build up a history of tectonic deformation and seismic activity. The ability to install new sensors and test new hypotheses using the stable infrastructure of cabled ocean floor observatories will greatly improve our ability to understand the processes involved in dynamics of the lithosphere.

Scientific questions that require cabled time series

(1) Deep-earth

The following questions all have incomplete answers that continuous time series data from remote parts of the ocean floor could greatly contribute to: 1) What are the properties of the earth's core? While we know much about the fluid outer core and the solid inner core, a lack of paths that pass through the deep earth to seismometers in remote parts of the earth (especially the southern hemisphere) hampers analysis. Indeed, a high-resolution image of the core is impossible now because data gaps render tomographic solutions for the mantle incomplete; this prevents precise ray-tracing through to the core. In the geomagnetism realm, we don't really know what causes the earth's magnetic field to reverse. Magnetic and electrical data from remote areas of the earth would help us find out. 2) What are the properties of the core-mantle boundary? Is the layer directly above this boundary the source of mantle plumes and hot spots? Is it the graveyard for subducted plates? Are the long wavelength geoid anomalies created by undulations in the core-mantle boundary? 3) What is the extent and structure of mantle convection? How is convection modified by subducted slabs? How much coupling is there between the tectonic plates and convection in the mantle? What is the role of mantle plumes in convection? What is the role of lithospheric roots under continental blocks in convection? How rapid is convection? How complete is mantle mixing?

(2) Regional dynamics and neo-tectonics

Answers to the following questions would be possible with long-term monitoring of plate boundaries and interiors: 1) How do the stresses and deformations across oceanic plates vary in space and time? When a large earthquake occurs, the deformation near the fault zone can now be measured on land using synthetic aperture radar satellite data. On the ocean floor, similar information could be obtained from strain meters, pressure sensors, and geodetic measurements that are now made only rarely in time and only in a few locations. In addition, the characteristics of small earthquakes – their location and fault motions, provide considerable information on the state of stress in a region. Only the largest earthquakes under the ocean floor are detected by existing seismic stations, and most data are too sparse to accurately determine fault location or motion. While acoustic arrays are now used to detect relatively small earthquakes, the acoustic data do not yield information on faulting. 2) Do gaps in seismic activity herald the occurrence of a large earthquake? Coupled with the data from historical earthquakes, monitoring of the great fault zones that rim the Pacific could greatly improve our ability to assess the earthquake hazard in these regions.

While there are many other regional structural problems that can be addressed by ocean bottom observations, the structures to be studied change their character very slowly (over thousands of years), and solutions to these problems, such as the structure of mantle plumes, will be best studied by large numbers of instruments deployed in different locations for short periods of time.

(3) Volcanic Processes

What is the nature, extent, and variability—both in space and time—of submarine volcanism? We know almost nothing about more than 80% of the earth's volcanic activity because it occurs at the deep-ocean floor. The structure of the spreading centers where most of this activity occurs is known only in the few places where intense studies have been made, but even in those places we have little more than snapshots of the mechanism that forms and modifies the ocean floor. New crust is added to Earth's surface at a rate of more than 1.5 km^2

per year, fast enough to form all of the ocean floor on earth in the last 200 million years. The spreading centers are the sites of hydrothermal, magmatic, and biological processes that we did not even know existed 40 years ago, yet we now believe that these processes are responsible for major mineral deposits and an ecosystem that may pre-date all other life on earth.

Submarine volcanism is also known to occur at hot spots where relatively fixed, buoyant plumes of upwelling mantle material form strings of volcanoes such as the Hawaiian-Emperor chain. Many of the submarine volcanic processes could be more easily studied at hot spot volcanoes than at spreading centers, since the volcanism is more likely to occur at a single point than along a line.

Strategies for Implementation

(1) Remote observatories:

The deep-earth structural problems mentioned above require continuous measurements at remote locations in the earth's oceans, often far from land and in places where weather and logistics allow only rare visits. For this reason, observatories in these regions must require very low maintenance and be able to withstand severe weather. Observatories cabled to land satisfy these requirements by providing power to experiments, information on the status of sensors, high data rates without need for periodic refueling, and no requirement for exposure to severe weather. Buoys, on the other hand, will require periodic refueling and will be exposed to severe conditions. The disadvantages of cabled observatories are the high up-front cost of cable – roughly $10,000/km – and of installation. These tradeoffs argue for a combination of cabled observatories for sites within some crossover distance of land (perhaps several hundred km) and buoyed observatories for more remote sites. Below we describe an exception to this: the reuse of retired telecommunication cables.

While the specific design of a seismic array within a cabled observatory would be governed by additional constraints, it is reasonable to consider arrays on land as a starting model. A standard for seismic arrays for observation of distant earthquakes is currently set by nuclear treaty monitoring. It uses arrays of sensors with an aperture of about 7 km around a central element. In the marine context, it would be desirable to augment this by an array of 1 km aperture for analyzing slower acoustic signals. Each circle might contain seven elements. Such an array would allow determination of the phase and group velocities of observed signals as well as beam forming. Each element of the array would contain broadband orthogonal seismic sensors sampled at 500 Hz and a hydrophone sampled at 2 kHz.

In addition to seismometers, other sensors, to collect magnetic and geodetic data, for example, would supply critical data and fulfill the observatory's promise of providing data to study linkages among varied data types. The geometry of the seismic array is not unlike that of an array of high-precision transponders used in GPS/acoustic links between the seafloor and land. A buoy (in the case of a buoyed observatory) or a ship simultaneously records GPS signals and acoustic ranges to an array of transponders, allowing centimeter precision positioning of the seafloor array in a GPS reference frame.

<u>Requirements:</u> High reliability, low maintenance, and continuous data. Science will likely require bit rates on the order of 10-20 Mb/s or more (10 Mb/s for seismology and acoustics alone). Land-based seismic arrays and single stations number in the hundreds around the world. The oceans, particularly the polar regions, are poorly covered. The justifications for

placing 25 stations in the oceans are found in "Broadband Seismology in the Oceans" published by Joint Oceanographic Institutions (JOI) in 1995.
Technical challenges: Installation and maintenance in high latitudes; requirement for conforming to Synchronous Optical NETwork (SONET) protocol or Plesiosynchronous Digital Hierarchy (PDH) on the older optical cables; and deployment of long (km+) cables at the ocean floor.
Logistical and practical challenges: Scheduling and availability of resources (ships and submersible assets) when needed for remote locations.

(2) Plate boundary observatories:
The primary functions of plate boundary observatories would be to monitor the temporal changes in all aspects of boundary phenomena, including deformation, earthquakes, and volcanism. Towards this end, probably the most important sensor system is the seismic array for location of earthquake and volcanic activity along the boundary. Such a system might consist of arrays of five nodes, each equipped with short-period seismic and acoustic sensors distributed about 50 km apart or closer along a plate boundary, with one node at each array housing broadband seismic sensors. This system would be too sparse for precise determination of depths and structures, and mobile arrays would likely be needed for deployment in areas of enhanced activity. Regional acoustic arrays, such as the Navy hydrophone arrays and equatorial hydrophone array operated by NOAA's Pacific Marine Environmental Laboratory can be particularly valuable for locating increased seismic activity in distant locations. Both earthquakes and volcanic activity can be located using arrays similar to the hydroacoustic arrays now being installed for Comprehensive Test Ban Treaty (CTBT) monitoring. Use of these data would provide scientists with locations where intense monitoring would provide the maximum benefit in the short term.

An experiment of particular value at spreading centers would be a linear array of 11 or more short-period vertical geophones extending about a km to each side of the ridge crest. This array would be able to detect small, time-lapse changes in the structure of the ridge as deformation and/or intrusive activity occurs and would be linked to systems to detect and sample fluids resulting from such activity.

Requirements: Distributed nodes along a long cable, real-time data, rapid response to events.
Technical challenges: Environment: survival of cables on rough bottom, sensor burial or drilling of shallow boreholes in hard rock, deployment of long (km+) cables at the ocean floor. At subduction zone boundaries, survival of cables running parallel to the boundary would be a serious problem on and near steep slopes where submarine landslides would be likely to cut the cable – particularly during the most interesting events.
Logistical and practical challenges: Scheduling and availability of resources (ships and submersible assets) when needed.

(3) Submarine volcano observatories:
In some locations, such as Axial Volcano and Loihi Volcano, volcanic activity is more likely to occur than in others in a given period of time than along any section of a spreading center. Such sites are prime targets for permanent observatories, since the probability of observing a complete cycle of activity is far higher than in most other places. These sites are more restricted in aerial extent than plate boundaries, and thus can likely be serviced by a single cable from shore which "spiders" (radiates) out or loops to several science nodes at the end of the cable. The topology of such an observatory would depend strongly on the characteristics

of the volcano, with seismic and acoustic arrays playing a major role in the detection and location of swarms and volcanic activity.

Requirements: Real-time data, rapid response to events, flexible (e.g. “spider”) topology.
Technical challenges: Environment: survival of cables on rough bottom, sensor burial or drilling of shallow boreholes in hard rock, deployment of long (km+) cables at the ocean floor.
Logistical and practical challenges: Scheduling and availability of resources (ships and submersible assets) when needed.

Cable re-use

Two factors could potentially decrease the cost of cabled ocean bottom observatories; first are the severe problems in the telecommunications industry which are reducing the cost of new cable, and second is the imminent retirement of the early trans-oceanic fiber optic cables. Cable can be obtained at far lower prices today than was possible a few years ago, particularly if the user can be accommodated by cable that has already been manufactured but not sold. Optical fiber cable systems installed in the 1980’s have become obsolete because of improvements in optical transmission technology. While the available data bandwidth is orders of magnitude lower than that of newer cables, it is orders of magnitude higher than can be obtained by satellite transmission or by coaxial cables. Such cable systems are thus of great potential value for ocean bottom observatories. Over $600 million in cable assets will be retired within the next few years; more than 22,000 km of cable in the central Pacific Ocean and a cable running from New Jersey to Europe. While these cables could be used in-place (as was done for the Hawaii-2 Observatory), it may also be practical to move cable segments to areas of particular scientific interest. In one scenario, eleven new ocean floor observatories, including two in the Southern Ocean, could be wired to shore (Figures 2 and 3). Another advantage of cable re-use is that the shore-end of the cables are already terminated at cable stations where power and data facilities are available, saving millions of dollars in installation and permit costs.

Power systems

Power supplied to a cabled observatory is limited by the length of the cable and the architecture of the electrical load. Each node on a cable will remove some of the available power from the system, and power used by the nodes most distant from the power source will “cost” the most in terms of the total power budget. Thus, if the primary science is far from shore, it may not make sense to have other nodes closer to shore taking power from that science. It may be more practical to run two cables with separate power, one for near-shore science, and one for more distant science. The fiber-optical cables presently available for re-use have electrical resistances of 0.7 ohm/km and operate at about 1.5 amps and voltages up to 8 kV. After losses in the cable and repeaters, well over 5 kW (about 4 average American households) of continuous electrical power could be available for observatory use 2000 km from shore. This topic is ripe for additional research, particularly to derive the optimum benefits from the re-use of retired telecommunications cables.

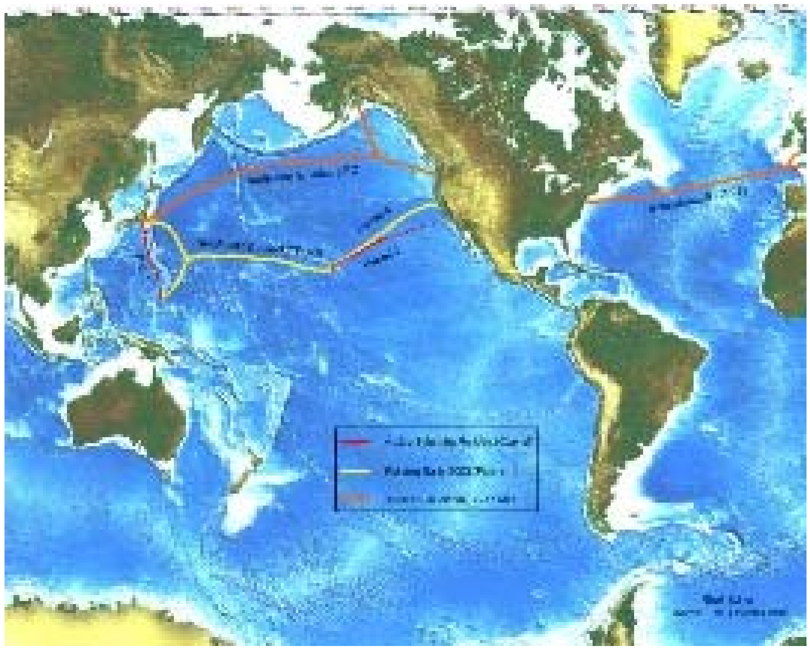


Figure 2. Locations of fiber optic cable systems about to be retired by the telecommunications industry. The cable in the Atlantic has already been retired.

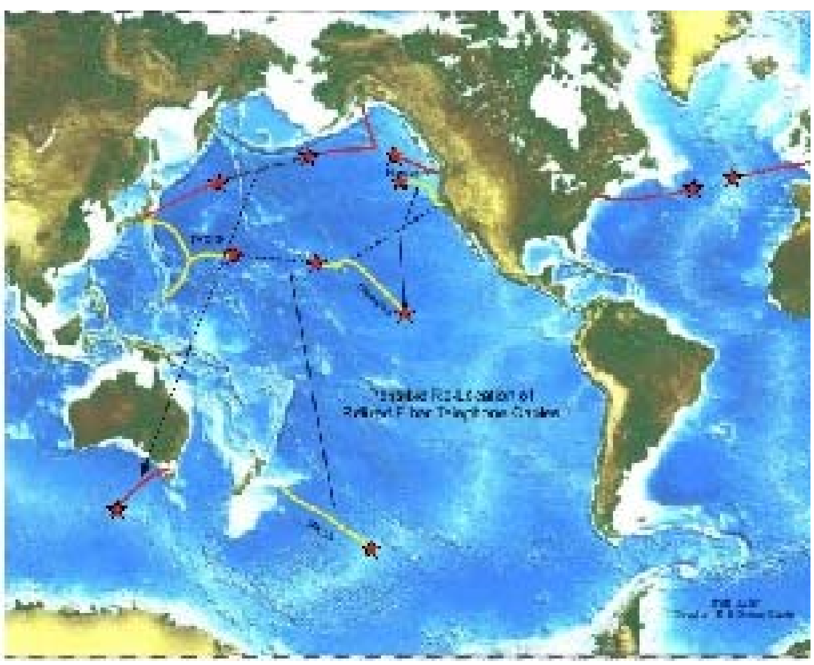


Figure 3. Possible observatory locations (stars) using the retired cables above. Two cable segments shown after movement from their current locations to sites in the Southern Ocean. This scenario establishes eleven observatories in remote locations.

Synergies

Siting observatories in the deep ocean will be a multi-disciplinary process. Geophysicists will desire a location that best fills a gap in global coverage of Earth, or a site near an active plate boundary or volcano, while physical oceanographers may prefer to select a site based on proximity to a major current or deep water pathway, biologists will be driven by microbial abundance and ecological questions, and chemists search for fluxes of important constituents of seawater. All, however, will benefit from the availability of a reliable infrastructure for data collection in real time and provision for continuous electrical power. A generic site which encompasses the interests of a large cross-section of sub-disciplines, including geophysicists, chemists, biologists, and physical oceanographers, will be one adjacent to a mid-ocean spreading center. Comprehending the relationships between many observables and uncovering the linkages between varied processes is best performed via cross-correlation analyses of accurately and continuously recorded time series.

Any consideration of site location must support many scientific pursuits that can take advantage of the infrastructure provided by a multi-use observatory at that location. An observatory installed for submarine volcano monitoring, for example, can (and should) also provide the potential to collect data on distant earthquakes, tsunamis, whale migration, ocean currents, ocean chemistry, and other unrelated phenomena. The synergy is provided automatically by the availability of the infrastructure as well as by preconceived linkages between experiments. Much of the benefit of a permanent observatory will be to provide sensors that will allow new linkages to be detected. Real-time geophysical monitoring will provide the opportunity to respond to seafloor events (e.g. eruptions, slumps etc.) that could impact fluids, life, and ecosystem dynamics, as well as make geological and geophysical changes to the system.

Where should observatories be installed?

Remote-site cabled observatories:

These observatories require the use of long cables, probably best supplied by optical cables that will be retired within the next few years. It appears feasible to relocate parts of these cables – possibly thousands of km in length to remote locations of particular interest, such as on the Pacific-Antarctic ridge. Such an observatory would require strong international cooperation. We strongly recommend that NSF take advantage of this opportunity to expand the ocean observatory network. Other sections of these cables could be used to establish a cabled observatory on the mid-Atlantic Ridge and North Pacific observatories south of the Aleutian Islands.

Plate-scale cabled observatories:
By far the easiest spreading center for the United States to consider for a cabled observatory is the Juan de Fuca plate (e.g., ridges and subduction zones). The activity of this system is well documented, and its proximity to the U.S. west coast makes it the obvious choice for the first cabled plate-scale observatory. Covering the entire plate rather than just the ridge provides a significant challenge. The scientific value of such an endeavor is enticing, yet one must never lose sight of the magnitude of the technological hurdles involved.

Submarine volcano observatories:
Axial seamount on the Juan de Fuca ridge is the obvious site for a submarine volcano observatory, and could easily be made part of a Juan de Fuca Ridge observatory. Another site of particular interest and logistic simplicity is Loihi volcano southeast of the island of Hawaii. Loihi is an active hot spot volcano located only 35 km from land with a summit 1000 m below the ocean surface.

Science Box 1: Sample Cabled Observatory Topologies for Lithosphere Studies

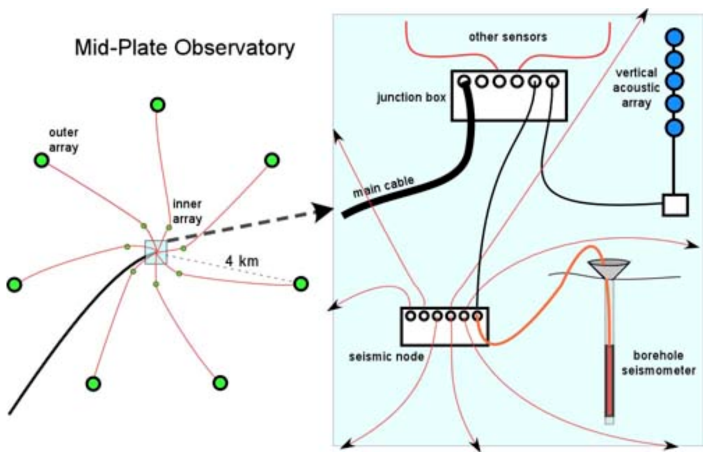


Figure 4a: Geophysical nodes for a remote-site observatory.

The remote observatory (Figure 4a)consists of two rings of seven sensors each, one at seven and one at one km from the center. A borehole seismometer and acoustic array could be located at the center together with other environmental sensors, buried broadband seismic sensors and geodetic instruments at each of the other nodes. This observatory would be capable of obtaining high quality geophysical data at a remote site for years at a time without maintenance. The multi-ring array of sensors makes it possible to obtain seismic phase velocity and directionality to earthquake sources. The acoustic array will be used for communication, navigation, acoustic tomography, and ambient, earthquake and biological sound detection.

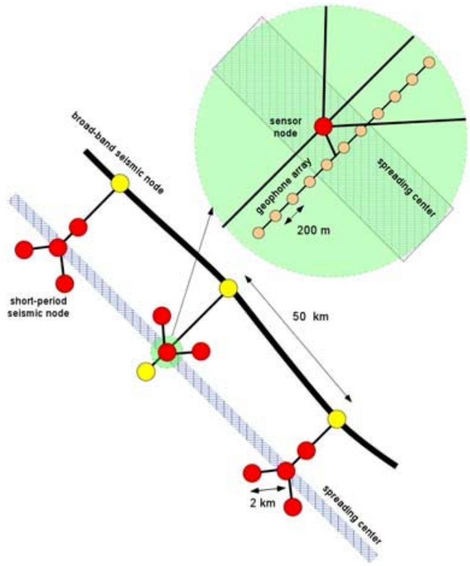


Figure 4b: Geophysical nodes for a spreading center observatory.

A ridge crest observatory (Figure 4b) might consist of nodes spaced every 50 km (closer would be better). Each node would contain an array of short period seismometers (red circles) and one or more broadband seismic sensors (yellow circles) for location and characterization of earthquakes as well as geodetic sensors to monitor deformation. A short period linear array would cross the active rift to monitor changes in shallow structure that might result from magma intrusion. These nodes would use junction boxes for connection of sensors on the ocean floor, and thus could accommodate experiments from any discipline.

2. Fluids and Life in the Oceanic Crust

Introduction

A new and rapidly growing area of scientific discovery considers how microorganisms utilize and alter chemical and mineral resources and contaminants in the diverse geologic substrates of the Earth's crust. Since oceanic environments are subject to hydrologic, thermal and tectonic perturbations, relationships have been proposed between these external driving functions, changes in crustal fluids, microbial populations and ecosystem dynamics. A potentially vast biosphere beneath the ocean floor may thrive by a wide range of metabolic lifestyles. The available observational data are frustratingly sparse, however, making it difficult to verify the critical energy sources and environmental linkages.

A multi-disciplinary observing system based on an underwater fiber-optic telecommunications network could enable investigations of some of the most far-reaching questions concerning fluids and life in three important and biologically complex oceanic provinces: ocean ridges, continental margins (especially outer shelf and slope regions), and nearshore coastal zones. Each of these provinces may be subdivided by factors relating to tectonics, sediment cover and ocean physics, but within and across sub-environments, each province is known to exhibit sub-seafloor and seafloor expressions of fluid flow. For example, recent studies of ocean ridges suggest that episodic changes in heat or volatiles in association with magma emplacement may drive expulsions of hot mineral-laden water that spark population explosions in the subsurface microbial biosphere and carry deep-living microbes into the ocean in large buoyant plumes. Convergent accretionary margins may host massive layers of methane hydrate (a crystalline solid consisting of gas molecules, usually methane, each surrounded by a cage of water molecules that looks like crusty snow; Figure 5) just a few centimeters to hundreds of meters below the seafloor. Gas hydrate destabilization and fluid seepage may trigger turbidites (density currents of sediment and seawater), fuel chemosynthetically based benthic communities, and produce carbonate precipitates (chimneys and slabs) or pockmarks that act as important habitat for declining commercial groundfish populations (see Science Box 2). Environments close to shore may exhibit enhanced benthic or water column productivity (including algal blooms) in response to groundwater inputs of nutrients and methane. On the continental shelf, periodic waves and tides may modulate hydraulically driven groundwater fluxes and may pump oxygenated seawater and suspended organic matter significant distances into permeable sand beds (refer to Coastal Section). These beds may then support high rates of microbial activity with influences on the whole shelf ecosystem.

Major Scientific Questions

By virtue of the power, data communications, and interactive monitoring capabilities available through cabled observatories, there are many fundamental scientific questions that could be addressed for the first time. The broadest of these questions in the realm of fluids and life in the oceanic crust is: *What forces and processes drive change in the structure and extent of the subsurface biosphere?* It is difficult to infer linkages between processes without observing changes in a system. It is also difficult to verify response times and scales of influence without nearly continuous, long-term, and spatially distributed observations of sensitive variables. Change may be imposed by anthropogenic utilization of the marine environment (e.g., by CO_2 sequestration, dredge-spoil disposal, or fishing activities) or it may be caused by natural events (e.g., major storms, magmatic and tectonic events, climatic shifts). The likelihood of biological feedbacks raises two other crosscutting questions: *How does sub-seafloor biological activity affect pore fluid chemistry, circulation, and fluxes to the greater ocean? What are rates of biomass production by chemosynthetic processes?*

Research directions and questions that are specific to an oceanic environment are given below. These examples are meant to highlight only a few areas of focus that could advance rapidly within a cabled observatory program.

(1) Ridge/Hydrothermal Systems

Pioneering time-series studies at mid-ocean ridges have shown earthquakes located over 200 km from a marine hydrothermal field may perturb hydrothermal fluid circulation patterns and fluxes of heat and fluids. Applied more widely and with innovative chemical and biological sensors, time-series observations could determine the geobiological impacts of magmatic and tectonic events, and they could be used to test hypotheses of event plume formation, to study how the magmatic/tectonic perturbations affect and alter the sub-seafloor and ocean biosphere, and to learn how they contribute to global biogeochemical cycles.

(2) Continental Margins

Gas hydrate deposits and fluid expulsion are common occurrences at all continental margins with thick sedimentary sequences, but tectonic convergence is the major force implicated for triggering catastrophic gas hydrate destabilization events (Figure 5). Key science questions that could be addressed with cabled observatories strategically positioned on continental margins are: How do rates of gas hydrate formation and dissociation respond to perturbations of pressure, temperature, fluid chemistry, and flow rate? What are the influences of gas hydrate formation and dissociation on ocean and atmospheric chemistry, biology, and climate? And to what extent do biological processes control hydrate formation and dissociation?

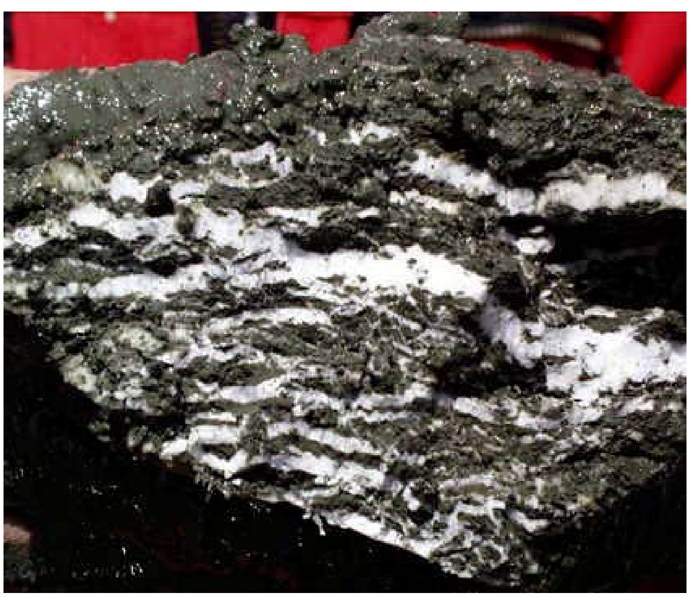


Figure 5. Thick zones of interlayered methane hydrate and sediment on continental margins comprise a vast fossil fuel reservoir. When hydrates destabilize, the release of large volumes of methane gas may cause slope instability, fuel unique seafloor communities, and contribute as a greenhouse gas to global warming. Future studies will require documenting chemical and fluid fluxes arising from hydrate destabilization.

(3) Coastal Zones

The coastal zone issues that are connected to crustal biogeochemistry concern the transport of chemicals (including pollutants) and microorganisms (including pathogens) into and within the marine environment. Overarching questions that may be addressed with the extended sampling presence of cabled observatories are: How is the community composition and activity of microorganisms in coastal sediments and impinging aquifers affected both in time and space by hydrogeology, terrestrial versus marine inputs, organic matter supply, and other environmental variables? To what extent do higher trophic levels in coastal ecosystems depend on the biogeochemical processes and production in coastal sediments?

Observational Strategies and Technical Requirements

The science questions outlined above require detailed geophysical and biogeochemical mapping efforts, long-term and reliable environmental and seismological time-series measurements, responsive event sampling, and experimentation at a small number of geologically diverse sites (e.g., focus sites exhibiting permeable sediments, gas hydrates, groundwater expulsion, and hydrothermal circulation
). The goal will be to track and cross-correlate changes in sub-seafloor, seafloor and water-column processes or conditions on time scales of seconds to decades. Although several design strategies could satisfy these requirements, single cables that branch, “spider”, or loop out to several science nodes (as described under Earth Structure and Dynamics) should be sufficient for most studies of subsurface biogeochemistry.
The kinds of fluid and biological variables that need to be targeted are concentrations of oxygen, methane and other small molecular weight hydrocarbons, species of inorganic carbon, sulfur and iron, pH, temperature, salinity, pressure, flow rate, turbidity, microbial community composition, and measures of microbial activity. Sensor installation both at the seafloor and in boreholes, sensor reliability, dynamic range, fouling, and the attraction of organisms to permanent structures are among the most significant technical issues to be overcome before long-term data sets can be collected for many of these variables. In the near future, repetitive short-term sensor deployments will still have great value. Small bore hole drilling may also prove useful for the deployment of rapid response sensors.

Sensor development programs will have to adhere to standardized power and communication interfaces for sensor packages but should also anticipate

the power, bandwidth, duration, and real-time intervention capability of cabled observatories. For example, at observatory nodes, power-demanding but effective anti-biofouling strategies such as mobile sensors placed on AUVs that can “hide” from organic or mineral-laden fluids, redundant sensor strings, or sterilization methods for sensor surfaces could be implemented.

Responsive event sampling, process studies, and experimentation may be accomplished by combined approaches. Mobile and/or robotic observatory platforms (relocateable moorings, ROVs, Rovers, and “lab benches”) could be brought in and/or activated in response to some kinds of events such as a new undersea volcanic eruption or test experiment of CO_2 disposal in the deep sea (Figure 6a). Pop-up samplers or samplers interfaced with AUVs will be especially important for retrieving microbial samples for laboratory characterizations. Modern support ships for launching, recovering and tracking these platforms and devices would need to be available to the community, and occasional rapid response scheduling would need to be possible.

Figure 6a & 6b. Remotely operated vehicles (ROVs) may serve as important tools for sampling at cabled observatory sites. Copious outpourings of white flocculent material called "snowblowers" are a distinctive form of low-temperature hydrothermal vent. Unlike high-temperature black smokers, where the suspended material in the "smoke" is tiny mineral particles, the "snow" is biological in origin. It is a byproduct of a microbial bloom in the subsurface hydrothermal system. Observatory studies may help determine how volcanic eruptions invigorate the subseafloor biosphere and create these blooms. The top image is a virtual image and the bottom image is a photo from Axial Caldera.

Synergies

All research that focuses on fluids and life in the oceanic crust will contribute to an understanding of the structure of marine ecosystems, will help define global biogeochemical cycles, and will begin to determine how geophysical events perturb and shape subsurface life-supporting systems. It is clear that ecosystems that depend on seafloor seeps and hydrothermal vents are unique because they are regulated by chemistry rather than light.

However, iron fluxes from hydrothermal vents may also ultimately limit photosynthetic primary production in a significant portion of the ocean. Sedimentary carbon pools on margins may regulate climate change, especially if methane from gas hydrates transfers to the atmosphere in significant volumes. In coastal areas, the turbulent benthic boundary layer impacts seafloor life and *visa versa*. Circulation and global dynamics at the plate-scale and local scale are certainly forces that trigger change in sub-seafloor and seafloor environments.

These thematic synergies can be developed through new and existing cooperative programs. International and national programs such as the Global Ocean Observing System (GOOS), Ridge InterDisciplinary Global Experiments (RIDGE 2000; a community-based science initiative focused on integrated geological and biological studies of the Earth-encircling mid-ocean ridge system), MARGINS (a research initiative focusing on geologic processes on continental margins supported by the NSF), and the Ocean Drilling Program (ODP) ensure coordination and communication to the scientific community and public. Facilities and national service agencies such as the Global Seismographic Network, and NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) offer other observational and data management services and models.

Science Box 2: Pockmarks, Seeps and Carbonates

Dives with the Remotely Operated Platform for Ocean Science (ROPOS, a remotely operated vehicle) on Hecata Bank and its seaward slope off Central Oregon have discovered multiple seep sites in water depths from less than 100 meters to 500 meters. These sites can be grouped into at least three types: A, B (Figure 7) circular pockmarks up to 5 meters deep within muddy sediments associated with bacterial mats and gas bubbling, C, D cemented mudstone outcrops showing streams of gas bubbles and carbonate mounds, and E, F extensive carbonate pavements with patches of *Calyptogena pacifica*. The overall impression from these observations and from water column measurements of methane is that methane seepage is an important geological and biological process on the upper slope and outer shelf region off Oregon (<500 m), and that seep areas constitute essential fish habitat for a variety of species that require complex structure.

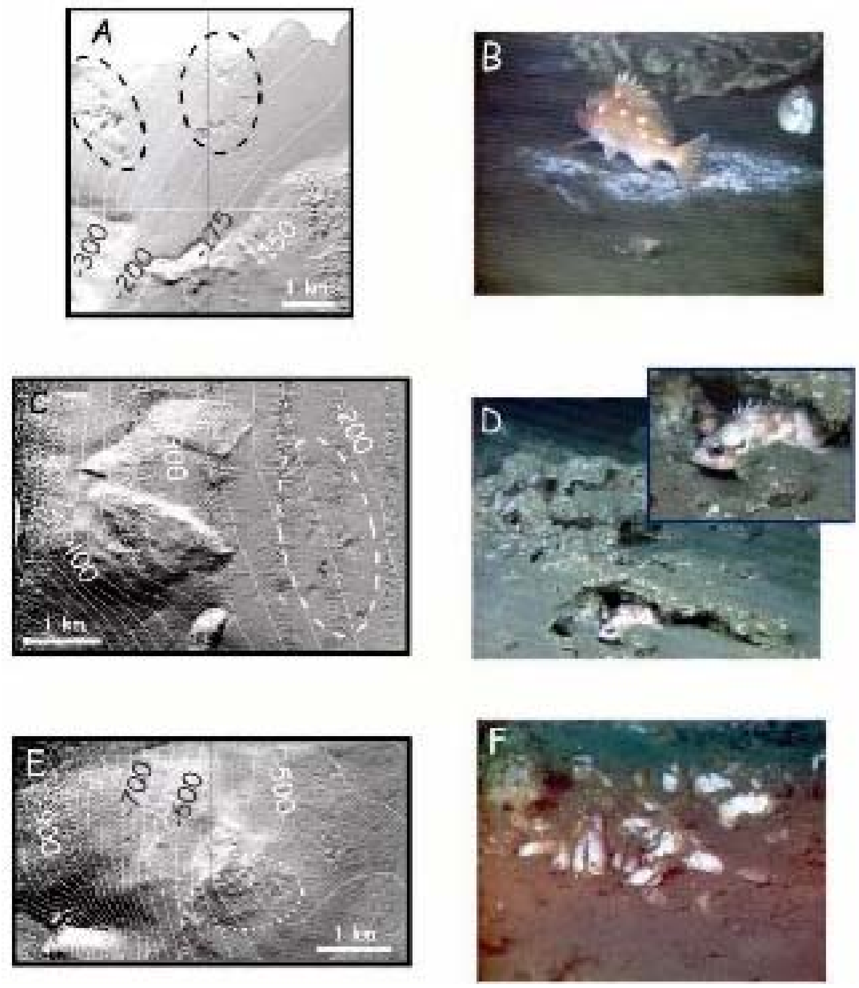


Figure 7. Sun-shaded bathymetric relief maps and associated ROPOS ROV images illustrating pockmarks, fluid seeps, carbonates and fish habitat in circled areas (left images) of a rocky bank on the continental margin off central Oregon. A, B rosethorn rockfish associated with a seep bacterial mat; C, D sharpchin rockfish within carbonate mound; E, F a 2 X 0.5 km rock outcrop at a water depth of 500 meters characterized by extensive carbonate pavements and concentrations of the bivalve, *Calyptogena pacifica.*

3. Coastal Ocean Processes

Introduction

The U.S. coastal ocean receives significant inputs of buoyancy, sediments, nutrients and other materials from rivers and is impacted, sometimes critically, by reduced water quality in response to these inputs. Seasonal hypoxia and the occurrence of harmful algal blooms (HABs) are chronic problems. Storm-driven currents, waves and surges also characterize the coastal ocean creating beach erosion, coastal hazards and flooding. The coastal regime is energetic, temporally variable and may be undergoing subtle changes (e.g., sea level rise, reduction in sediment supply) in response to climatic cycles and long-term changes. Because of the complexity of coastal environments, accurate, spatially distributed and integrated observations, sustained over many years or decades and linked to sophisticated numerical models are needed. The integration of cabled observatories, at selected regional sites, into a more comprehensive and broadly distributed national coastal observing program would offer an infrastructure for addressing some highly compelling and cutting edge scientific questions that cannot be adequately addressed without the large bandwidth and continual power supply that cabling allows.

Among the fundamental scientific issues are improved understanding of: turbulence and water column mixing; benthic processes; air-sea interaction; decadal changes in climate; upwelling and downwelling; storm-induced coastal processes; and the impacts of river inputs. A major theme relates to sediment transport, pollutant fluxes and coastal water quality under a wide spectrum of energy conditions. Additionally, such integrated architecture would provide a unique work bench for numerical model skill assessment and data assimilation. Cabled observations in support of coastal oceanography are essential for several reasons: (1) Threats to moored instruments are acute during severe storms in the coastal ocean and cabling helps to assure that data will be retrieved if instruments are damaged or lost. (2) Capturing data on turbulence, nutrients, suspended sediment concentration, multi-wavelength optics, multi-frequency acoustics, and video imagery requires high bandwidth. (3) Many sensors and sampling devices require large power supplies that can only be provided by cables. (4) It is important to obtain real-time data during severe storms such as hurricanes for assimilation into models for operational needs. (5) Sensor utilization (e.g., acoustic Doppler current profilers (ADCPs), acoustic Doppler velocimeters (ADVs), multi-frequency acoustics, multi-spectral optics, and video systems) could accelerate if the inherent problems associated with large power requirements and rapid delivery of large volumes of data could be solved; cabling could eradicate these problems.

Science Topics

There are numerous new and compelling science questions pertaining to the U.S. coastal ocean. Two cross cutting scientific issues that pervade coastal science in most parts of the world include the effects of storms and river inputs. An additional issue, not included here, concerns the role and behavior of sea ice in coastal waters. The cross cutting issues relevant to mid- and low-latitudes are:

(1) How do the coastal ocean and atmosphere interact on synoptic scales during storms and on longer time scales?

This general question includes the following subset: (a) What are the patterns of heat and moisture flux during cyclogenesis and what influences the patterns? (This question is clearly linked to our ability to predict the development of coastal storms.) (b) What are the local and remote (i.e. forced and free) responses of surface and bottom currents to storms? (c) What is the vertical structure of storm-induced turbulence within the water column over the continental shelf? (d) How do weather patterns (event, seasonal, interannual) and climate change influence the timing, frequency, distribution, and transport of harmful algal events (including fish kills and increased public health risk)? And (e) to what extent do river flow, coastal currents, nutrient fluxes and biology change in relation to larger scale climate patterns?

(2) In what ways and to what degree does the ubiquitous presence of river-supplied buoyancy, nutrients, sediments and toxins in the coastal ocean impact or modulate the physics, chemistry, biology and geology of the system?

Included among the specific aspects of this question are: (a) What are the patterns and extent of transport of major, localized/regional inputs of dissolved material that may affect production (e.g. nutrients) or ecosystem "health" (e.g., pollutants)? (b) How will the variations in river flow, from anthropogenic or natural climate change, affect buoyancy-driven currents and the important role they play in ecosystem function? (c) How do coastal circulation patterns and the discharge of rivers interact to govern the timing and extent (time-space distribution) of bottom water oxygen depletion? And (d) how are surface and bottom current responses to episodic strong winds modified by the widespread presence of coastal buoyancy and what effect is imparted on wave propagation?

Within these broad issues is a select subset of questions that can best be adequately addressed via arrays of cabled sensors. These are fundamental, coastal specific topics. All are interdisciplinary. Key fundamental science topics include the following:

(A) *Water column mixing and vertical fluxes* – Understanding the vertical structure of turbulence and consequent mixing is crucial to effective modeling of coastal circulation, sediment transport and surface primary productivity. Water column mixing affects pollutants, oxygen, nutrient cycling, and water quality. Episodic storms play an important role. Vertical mixing impacts biology, chemistry, ecology and sediment transport. Sensor systems capable of sampling, non-intrusively, at the required temporal high frequencies and spatially fine resolutions currently exist but power consumption is large and data communication requires greater bandwidth than conventional telemetry can offer.

(B) *Benthic Processes* – Seabed properties are greatly affected by internal solitary waves, storms and episodic biological activity. Relatively few long-term observations exist that integrate high-resolution bed and boundary data. These data could bring about the next breakthrough of theory addressing complex wave-induced suspension over rough topography. Little is known about changes of seabed geotechnical properties during storms. Sector-scanning sonars detect bioturbation and modification of bottom roughness by macrofauna, but such systems are particularly data and power demanding. While much could be learned during short-term deployments, multiple or long-term deployments are required to obtain datasets during rare extreme events. Extreme events need to be observed in order to provide sufficiently large signals to differentiate between competing models that tend toward agreement during everyday conditions.

(C) *Air-sea interaction in the coastal zone* - Improved understanding of air-sea exchanges across a wide range of environmental conditions, under both low wind and high wind and in stable, neutral, and unstable conditions, are required to investigate the role of air-sea interaction in coastal dynamics. The coastal zone presents unique opportunities and unique challenges. Among the unique opportunities are the occurrence of cold, dry atmospheric flows over the water with attendant large air-sea heat fluxes, the potential for large air-sea exchanges associated with wave breaking, and the combined influence of regional variability associated with coastal ocean dynamics and regional and synoptic meteorological variability associated with weather systems and orography. Among the challenges are the integration of the influence of the surface waves into the work, the smaller scales of coastal variability, the presence of fishing and recreational vessels, and the need to acquire data at high rates at enough sites to resolve spatial variability. A cabled observatory that includes shallow-water surface-piercing towers with a number of sensor locations can provide direct flux measurements over the desired wide range of environmental conditions (including wind speeds in excess of 25 m/s, where little such data exists) and are able at the same time to make the surface wave measurements needed to understand and include sea state influences.

(D) *Decadal effects of climate change* – Intermediate-term changes in regional and global climate affect interannual cycles of stratification, bed morphology, directional waves, concentrations of nutrients, oxygen, and primary productivity. Sustained and reliable time series, especially during severe storm events would benefit from cabled sensors.

(E) *Across-shelf fluxes and flux gradients (convergence/divergence)* -The processes of upwelling and downwelling over continental margins generally are crucial to across-margin fluxes of sediment, nutrients, carbon, heat and plankton. Over the shelf, vertical flow segregations are important and require fine-scale vertical resolution. Across-shelf arrays of multiple sensors at different across-shelf locations are required to obtain the necessary data on gradients over extended time periods to explain depositional and erosional processes.

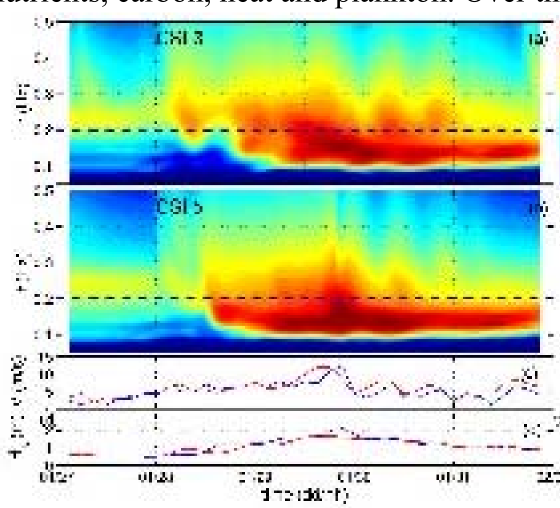


Figure 8. Time series showing the spectral evolution (a and b) of waves in the Gulf of Mexico during a storm; CSI 3 is a muddy coast whereas CSI 5 is considerably more sandy. The wind forcing (c) is similar at both sites whereas waves are attenuated (d) at the muddy site.

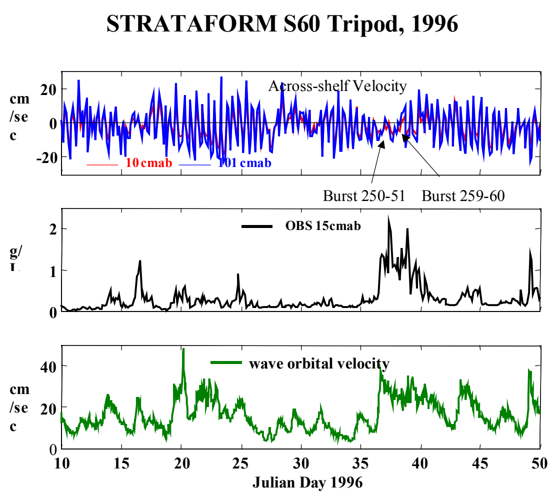
(F) *Dynamics of river and estuary plumes* - The patterns of buoyancy flux, effluent mixing and associated biogeochemical and biological properties off river mouths and estuary entrances are highly complex in both time and space. Although satellite data can provide valuable information about surface patterns under the right atmospheric conditions, cabled arrays of spatially distributed sensors are needed to provide three-dimensional data under all conditions including the most severe events. Additionally, harbor traffic and debris discharged by rivers are hazards to any platform with a surface signature and cables solve this problem.

(G) *Wave-current dynamics in heterogeneous environments* - Nearshore wave propagation plays a crucial role in determining the patterns of wave-driven currents, erosion and sediment deposition patterns. Nearshore wave evolution has been studied almost exclusively in sandy environments. However, heterogeneous sedimentary environments characterize many of the more dynamic and complicated coastal systems, such as large river deltas. Wave evolution in these environments is complex and not well understood (Figure 8). Cabling will ensure data recovery during extreme events.

Science Box 3: Benthic Processes

Studies of benthic boundary layer processes are among the numerous process studies that would benefit from cabled observations. Such studies are typically highly interdisciplinary and involve obtaining time series of near-bed turbulence and bed stress, changing patterns of bed roughness, suspended sediment concentration, velocities of oscillatory and mean currents, benthic biota and dissolved oxygen among other parameters. Science themes of such studies are diverse but most deal with some aspects of the complex time-varying linkages among near-bed flows, bed micromorphology, turbulent mixing within the bottom boundary layer, particle resuspension and epifaunal and infaunal interactions with the physics. Sampling multiple parameters at high frequency is essential to the success of such studies and acoustic and optical imaging is extremely data and power demanding. Communicating such data via high bandwidth cabling would greatly improve our ability obtain high-quality and sustained time series of poorly understood processes.

To date, most benthic boundary layer studies have been experimental and utilized internally recording bottom mounted instrumentation systems that yield short duration time series such as those shown in Figure 9. The duration and information content of such time series would be vastly improved by cabling. Figure 10 shows pronounced spatial contrasts in bed roughness as recorded by a single sidescan sonar transect. Comparable temporal variations in roughness can be recorded by sector scanning sonars provided that adequate bandwidth exists for data communication.



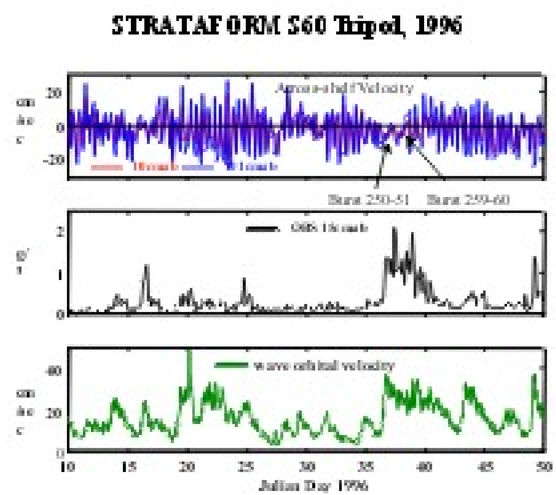


Figure 9. An example of time series of across-shelf mean current (upper panel), suspended sediment concentration (middle panel), and wave orbital velocity (bottom panel) as observed in the STRATAFORM study on the Eel River shelf in winter 1996. The data were recorded *in situ*.

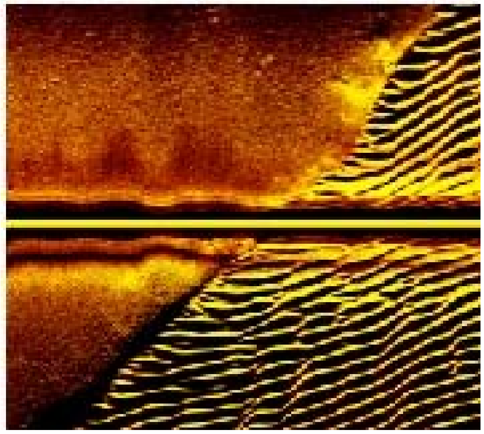


Figure 10. Side scan sonar image of spatially contrasting smooth (upper left) and rough (lower right) bed roughness patterns on the inner continental shelf. Comparable temporal variations can be recorded using rotating sector scanning sonars.

Sampling, Sensors and Methodologies

Implementation of cabled coastal observatories in different regions should be a phased process. An initial phase may involve integrating existing observatories. As a modest initial cabling deployment, a single cable might be laid from an existing shore landing out to the shelf break. At the start, the cable may support a minimal number of nodes. Adding nodes and cables can progressively expand an array. It is envisioned that relatively modest coastal observatories could serve as testbeds for deeper and more ambitious deployments.

Figure 11 illustrates the configuration of two (of numerous possible) coastal moorings. Table 1 lists some currently available sensors and the parameters that they will record. For physical measurements, bottom-mounted pods typically support pressure, conductivity and temperature sensors and an upward-aimed acoustic Doppler current profiler (ADCP) to measure currents throughout the water column. The ADCP system also allows the determination of directional wave spectra as well as indirect measures of water column turbidity (via acoustic backscatter intensity). Rapid continuous sampling of each individual "ping" can allow determination of turbulent spectra. Surface buoys or surface piercing towers can support meteorological sensors and *in situ* water quality sensor packages (Table 1). They also perform initial data processing and store both raw and preprocessed data and can telemeter data to shore stations in the event that a cable connection fails; however optical fiber cabling connecting the moorings to shore based data hubs will permit superior broadband connectivity.

Robust fixed surface piercing platforms can be added to the cabled observatory in shallow water. An array of such sites aligned perpendicular to the shore and transitioning to moored surface platforms offshore would, for example, provide the means to examine air-sea fluxes and their change as waves shoaled and broke. Fixed offshore sites could support vertical arrays of atmospheric sensors making direct turbulent flux measurements. Shore-based masts and towers on the same network could be used to extend the array inland. The shore-based systems can be used to directly measure air-sea exchange when the winds are onshore and the systems are situated close enough to the ocean's edge. Data from all sites would be recorded ashore, and the array of platforms could be readily serviced. While the offshore buoys and lowest sensors might not survive every storm, the fixed platforms would likely provide continuous observations that would allow us to extend our understanding of atmospheric forcing and air-sea interaction to include regimes under severe storms, tropical cyclones and hurricanes. Across all meteorological regimes, cabled arrays that could resolve alongshore as well as across shore oceanographic and meteorological variability would do much to improve our understanding of air-sea interaction in the coastal zone.

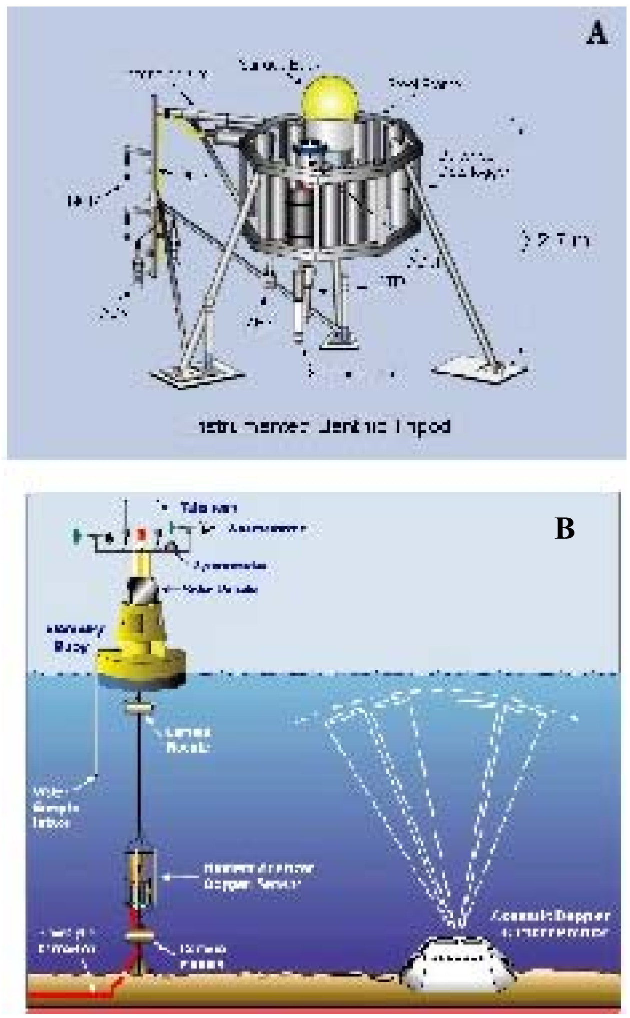


Figure 11. Examples of coastal observing hardware currently used. A. Bottom boundary layer instrumented tripod for measuring bed stresses, sediment resuspension, waves, currents etc. B. Coastal mooring supporting an acoustic Doppler current profiler, meteorological sensors, nutrient analyzers, oxygen sensors, and a fluorometer.

Table 1. Some Coastal Observing System Instrumentation

Instrument/sensor	Measurement	Variable
Acoustic Doppler Current Profiler (ADCP)	Current velocity and direction	Directional wave gauge
CT module	Conductivity, temperature	Temperature, salinity, density
Fluorometer	Chlorophyll *a* fluorescence	Phytoplankton biomass
Optical spectral absorption, attenuation, and backscatter sensors	Turbidity, spectral inherent optical properties	Several spectral inherent optical properties (e.g., related to chlorophyll, CDOM, detritus, phytoplankton species)
Optical spectral irradiance, absorption, and attenuation sensors; optical diffraction systems; and video	Spectral irradiance, absorption and attenuation coefficients; Fraunhofer light scattering; and video	Spectral light available for phytoplankton growth and vertical light attenuation coefficient; particle size distribution & concentrations; Video
In situ nutrient analyzer system	Colorimetric analysis and optical methods	Nitrate, phosphate and/or silicate concentration. Ammonia in development
Dissolved oxygen sensor	Dissolved oxygen concentration	Oxygen
Meteorological module	Winds, temperature, pressure, humidity, solar and infrared radiation	Meteorological parameters just above sea surface
Acoustic Doppler velocimeters (ADV)	Fluctuating and mean near-bed velocity components	Bed stress, near-bed turbulence, bed level
Acoustic backscatter sensors (ABS)	Suspended sediment particle concentrations	Near-bed variations in suspended sediment
Sector-scanning sonar (*in situ*, near-bed, rotating); Multi-frequency acoustic backscatter	Acoustic backscatter from bed roughness elements; Multi-frequency acoustic backscatter	Time-varying bed roughness, bed morphology, benthic organisms; zooplankton & particles or aggregations by size
Pressure sensors	Pressure fluctuations at bed	Waves, tides, storm surge

Synergies and conclusions

A vibrant cabled coastal observing program would build on major earlier continental shelf dynamics programs such as the Coastal Ocean Dynamics Experiment (CODE), Sediment Transport Events on Shelves and Slopes (STRESS), Coastal Mixing and Optics (CMO), Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) and Strata Formation on Margins (STRATAFORM) and could serve to integrate and enhance existing coastal research observatories. The coastal component would support and be highly complementary to other cabled observatory science issues including turbulence, ecosystem dynamics and biogeochemical cycling in addition to the science topics described above. The addition of coastal nodes to a deep ocean program could address coastal science topics at low additional cost. A few strategically placed cables located at sites off the Atlantic, Pacific, and Gulf of Mexico coasts would provide higher resolution than currently exists and provide significant new science opportunities. Cabled coastal observations could advance coastal science to a new plateau by facilitating rapid and dependable sampling of fluctuating and rapidly changing phenomena under all environmental conditions for long time periods.

Coastal cabled observatories equipped with physical/bio-optical sensors also can be used to develop and validate new satellite ocean color algorithms for complicated coastal waters, both for existing satellite sensors as well as the envisioned hyperspectral sensors. Real-time data from multiple locations within a satellite image could be used to calibrate algorithms, or, possibly depending on conditions, choose between competing algorithms when the satellite data products are generated. Combining the time series data from cabled observatories with other spatial data sets, and assimilating these into evolving numerical models, could provide improved predictions of phenomena of interest to operational stakeholders.

4. Turbulent Mixing and Biophysical Interactions

Introduction

Small-scale turbulence affects marine ecosystems in a variety of ways. In the surface layer of the ocean, large eddies of the turbulent field advect phytoplankton in strong near-surface light gradients, affecting the averaged light available for photosynthesis as well as residence times at potentially damaging UV levels. "New" nutrients can be supplied to the euphotic zone via vertical turbulent fluxes associated with entrainment deepening of the mixed layer and/or diffusion across the steep property gradients at its base. Turbulent shears affect the integrity of marine snow particles and net export flux of these and other biogenic particles, as well as the efficiency with which zooplankton sense and capture prey. Finally, the average turbulence level of a marine environment is hypothesized to be a major determinant of community structure, i.e. species distribution, as well as biomass. At the bottom boundary of the ocean, turbulence also affects benthic ecosystems. Community "re-sorting" is associated with episodic resuspension of the upper layer of sediments during storm/runoff events. Turbulent vertical transport resupplies nutrients to the sediment-water interface and moves eggs and larval stages of benthic organisms into the overlying water column, where they can be distributed spatially by mean flows.

Present (microprofiling) methods of small-scale turbulence in the ocean environment are sufficiently labor-intensive, hence expensive, that few biological process studies can afford the turbulence measurement component necessary for field studies of biophysical interactions. Moreover, even were this addition routinely possible, ship-based observational periods are too short to encompass the entire temporal range of processes involved in these interactions. Thus, despite the importance of the above (and other) questions involving interactions between small-scale turbulence and marine ecosystems, it has proven difficult to produce unequivocal observational evidence of suggested connections.

Applied to studies of the effects of turbulence on biological ocean processes, the promise of time series from ocean observatories is three-fold. First, both the ample power and broad bandwidth provided by cabled systems are essential for any of the present methods for measuring turbulence quantities (dissipation scales with microscale sensors or large-eddy scales with acoustics), and for those biological techniques (such as multi-frequency acoustics, multi-wavelength and sheet light optics, and video/still photography) that provide sufficient detail to adequately delineate ecosystem response. Second, the ability to measure turbulence and ecosystem properties continuously over long periods of time allows accumulation of multiple realizations of the interactions described above (and doubtless others). At the intersection of two sets of highly non-linear processes (turbulence and ecosystem dynamics), correlational analysis of such records may be the only statistically significant means of suggesting causal relations. The same time series will, of course, also illuminate the relative importance of episodic "extreme" events to various ecosystem characteristics. Finally, it is likely that extensive experience with temporally well-resolved fields at cabled observatory sites will eventually make it possible to suggest and evaluate statistically meaningful measures of turbulent and ecosystem quantities that can be made under the power and storage constraints associated with non-cabled systems.

Scientific questions that require cabled time series

Several outstanding questions about the influence of turbulence on marine ecosystems could be addressed using the high power, high data rates, and extended time presence that are the strengths of cabled observatories. The following paragraphs highlight three of these.

(1) Phytoplankton community structure

An overarching question concerns the role of turbulence in determining phytoplankton community structure, i.e. the mix of species that is characteristic of the large-scale biological "provinces" in the sea (see Science Box 4). Reduced to more local spatial scales, this is the same question of which species achieve the dominance that characterizes a phytoplankton bloom. How is the success of a single (or very few) species influenced by the interactions of individual phytoplankters with the myriad environmental factors, such as water column stratification, light and nutrient supplies, etc. that are strongly modulated by turbulence processes? A seemingly separate question - whether the *kind* of available nutrients is more important in determining phytoplankton community structure - is actually closely related, since interplay between turbulent motions and light fields can result in modification of the nutrient menu present at any particular location.

(2) Formation, dissolution and export of marine snow

Another major set of questions involves interactions between upper ocean turbulence and marine snow. It is hypothesized that increasing turbulence levels first enhance the formation of marine snow, by increasing collision rates of biological particles, but eventually begin to increase its rate of dissolution, as turbulent shears become sufficiently large that composite particles can be torn apart. Marine snow aggregates provide many functions in oceanic ecosystems, serving as habitat, concentrated food source, and/or vertical transport mechanism for a variety of organisms. It thus seems possible that temporal variability in the structure of marine snow, as determined by its turbulent environment, may play a significant and as yet under appreciated role in structuring marine ecosystems. Finally, the frequency of turbulent entrainment events at the base of the surface mixing layer is likely a controlling factor on the net escape of marine snow particles from the bio-active surface layer. Because marine snow makes a major contribution to the net carbon export to the deep sea, quantifying the effects of complex interactions at the mixed layer base is of importance to global biogeochemical cycling.

(3) Benthic community structure

A third major question is how the structure and variability of turbulent bottom boundary layers act to influence (perhaps even determine) structure of benthic communities. How is the underlying benthos affected by changes in the structure of the turbulent benthic boundary layer in the transition from continental shelves to deep ocean? How is the cross-shelf structure of the bottom boundary layer linked to net export of organic material from continental shelves? Since shallow coastal regions make contributions to organic carbon flux that are disproportionately large relative to their areal extent, and since export to the deep sea can result in long-term "storage" of carbon, the latter question is of fundamental importance to understanding the ocean's contribution to the global carbon cycle. Episodic events are likely to be major structuring influences, not only on the deep-sea benthos associated with eruptive events near the seafloor, but also on the benthos of coastal regions where surface (wind-driven) and bottom (current-and wave-driven) boundary layers may infrequently interact to produce extreme levels of benthic turbulence.

Significant advances in any of these three major research areas demand the power and bandwidth attributes of cabled observatories, coupled with their potential for continuous measurement over a period of time that contains several of the longest cycles thought to influence the turbulent and biological fields. This minimum time period will be of order several years for upper ocean biological communities dominated by the annual cycle or interannual phenomena, but may be far longer for both upper ocean and benthic communities, depending upon the importance of episodic events (and the frequency with which they occur) and of ENSO/decadal variability. Autonomous (non-cabled) moorings cannot provide the necessary power and bandwidth. Ship-based sampling cannot provide the necessary time extent. Freed from these limitations, cabled observatories offer the opportunity to make substantive advances in answering the three major questions outlined above, and doubtless many other outstanding questions involving interactions between oceanic turbulence and the embedded marine ecosystem.

Sampling strategies and sensors for cabled time series of biophysical interactions

Cabled observatories have the potential to provide measurements of essential turbulence and ecosystem quantities, adequately resolved both in time and in the crucial vertical dimension that contains the largest spatial gradients of these properties.

In considering the temporal resolution required, it is helpful to differentiate between the high ("characterization") frequencies required to achieve quantitative estimates of turbulent and biological fields, and the lower ("descriptive") frequencies at which such estimates are used to study questions like those outlined in the previous section. The lower descriptive frequencies depend on the particular process being addressed, but would likely be of order once per hour or fraction thereof (say ~ $1x10^{-3}$ Hz). This is very much lower than the base rates required to characterize either turbulence quantities, such as stresses from ACDPs (~ 1 Hz) or turbulence kinetic energy dissipation rate from airfoil probes (100 Hz), or ecosystem quantities, such as species composition from multi-frequency acoustics (~ 10s Hz) or digital photography/video (1000s Hz).

The actual data rate realized by a biophysical observatory will be a strong function of the vertical range/resolution (R/ΔR) required. While this too is a function of what processes are being examined, rough estimates can be made. A requirement for 10 cm resolution (ΔR) over a water column extent of 100 m (R), typical of both upper ocean and benthic active layers, implies that the above base rates increase by a depth factor of $O(10^3)$ if all measurements are made simultaneously at all depths. However vertical profiles of biophysical variables come from two fundamentally different types of instruments. The first are "inherent" profilers, - range-gated acoustic instruments such as Doppler profilers (ADCP) for horizontal current, or multi-frequency acoustic backscatter instruments (ABS) for estimating concentration/size of a variety of marine particles, including suspended sediment and zooplankton. A single such instrument, mounted on the seafloor, provides vertical profiles over ranges dependent upon acoustic frequency. The second type of vertical profile is provided by a point sensor that is periodically moved vertically through the water column by some kind of buoyancy controlled or mechanical device, such as an underwater winch. Most biophysical sensors that require high sampling frequencies for characterization (e.g. airfoil probes and high resolution video) are of this second type, so depth sampling actually occurs sequentially rather than simultaneously. In addition, profiles of this second type would not be made continuously, but on the much lower "descriptive" frequency (see (i) above). As a result, the multiplicative depth factor will be much lower than 10^3. Thus, with the possible exception of very high resolution streaming video, the net data rate for a biophysical observatory node should be considerably lower than that (~$9x10^6$ bits/s) being proposed for geophysical applications, and the time/vertical resolution necessary for examining biophysical interactions should be easily achieved by cabled installations.

The instrumentation thought necessary to address the problems outlined in the previous section can be classified into three categories.

(A) Commercially available instruments, using well-tested techniques: includes CTD, 4-beam ADCP, fluorometer, transmissometer, spectral light sensors, side-scan sonar, multi-sample sediment traps, and multi-sample water samplers/pumps.

(B) Instrumentation requiring further development (hardware, algorithms), and/or commercialization, before being operational in an observatory environment: includes oxygen sensors, nutrient sensors, video plankton recorders, multi-frequency acoustic and optical profilers, airfoil probes, 5-beam VADCP capable of measuring both mean and turbulent quantities, and an underwater winch or buoyancy controlled profiling system.

(C) Sensors that exist but are at early experimental stages: includes DNA sensors, holographic imaging systems, *in situ* water and sediment samplers and storage devices, and sensors for turbulent scalar fluxes.

Significant investment in instrument development will be necessary for all categories but the first. Both of the latter two categories of instruments would benefit from testing at observatory sites.

Finally, to fulfill the potential of cabled times series for problems of biophysical interactions, it is essential to design a sampling strategy that acknowledges and addresses the fundamental fact that a time series from a fixed location in the ocean provides temporally (and vertically) well-resolved measurements that are aliased by (horizontal) spatial variability in the underlying fields (the opposite problem is faced by ship-borne oceanographers, who typically make spatial measurements aliased by temporal variability). From the outset, sampling strategies for biophysical process studies at cabled observatory sites must include provision of spatial resolution sufficient to separate advective (spatial) changes from true temporal changes. To focus discussion of necessary sampling strategies, consider the prototype biophysical observatory shown in Figure 12, centered on a continental shelf node of the cabled network of Figure1[ER8]. At the central node, (P), a bottom-mounted underwater winch controls periodic vertical profiles of a full-suite sensor package (P). The package rises freely under buoyancy (enabling measurement of turbulence microscales with airfoil probes and macroscales from density resorting,

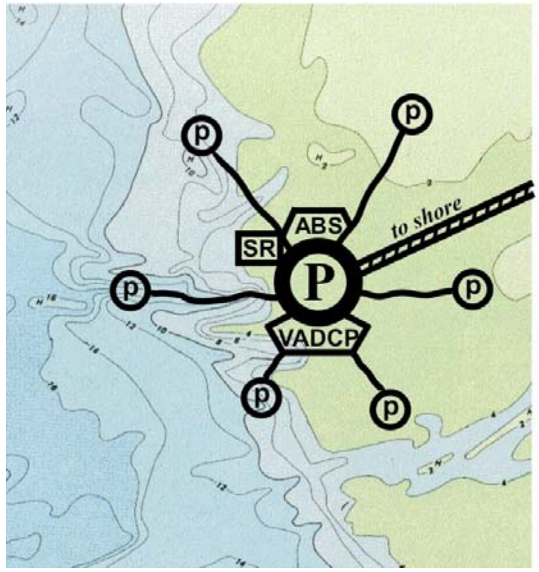


Figure 12: A prototype observatory for biophysical interactions, consisting of a full-suite central profiler (P: CTD, airfoils, fluorometer, transmissometer, light and nutrient sensors, video plankton recorder, and small-volume water sampler), plus sample repository (SR), "turbulence" VADCP, and multi-frequency acoustic backscatter profiler (ABS). This central position is surrounded by a number of reduced-suite ring profilers (p: CTD, fluorometer, and transmissometer) plus ADCPs, designed to allow estimation of advective contributions to the time changes observed at P.

as well as normal profile variables) and makes a series of programmed halts during winched return to the bottom (enabling biological community assessment with video/still photography and acquisition of small-volume water samples required for more specialized laboratory techniques). Co-located are a 5-beam Acoustic Doppler Current Profiler (VADCP) [ER9]for mean shear and turbulence quantities, multi-frequency acoustic backscatter instruments (ABS) for zooplankton and suspended sediment profiling, and a repository (SR) for storage of small-volume samples. The central installation is surrounded by a number (e.g., 6) of reduced-suite profilers (p) and standard 4-beam ADCPs, forming a ring with diameter of 100s of meters to a few kilometers depending upon the scale of process being studied. While this generalized topology can be adjusted for topographic constraints, dominant current structure, etc., t[ER10]he spatial resolution resulting from such a sparse array is admittedly coarse. However, provided the number and spatial disposition of ring stations as well as their distance from the central node are carefully determined through prior survey of topography, both mean and tidal flow fields, and property distributions in the area, measurement of horizontal currents and basic biologically-linked variables (fluorometry and spectral optics) at the ring stations should allow meaningful estimates of the magnitude of advective changes present in the time series measured at the central node.

Synergies

If coupled with the increasing power of process-based numerical modelling, an ability to make continuous measurements of both turbulent and mean flow fields under a wide range of physical forcing conditions presents the oceanographic community with an unprecedented opportunity to test and advance the simplistic turbulence parameterizations that are presently employed in intermediate- and large-scale ocean models. Since such models are uncomfortably sensitive to these parameterizations, observatory-based measurements of ocean turbulence are of fundamental importance to attempts to produce the reliable predictive model of the coupled ocean/atmosphere system that is essential for prediction of "greenhouse" changes in earth's climate, and in the embedded oceanic (and terrestrial) ecosystems.

A mix of intensive time/depth (t/z) sampling with coarse horizontal spatial (x/y) sampling, similar to that proposed here for addressing biophysical interactions, will likely be necessary for many or some of the other applications foreseen for cabled observatories. The approach described above was designed with a shallow application in mind, but could easily be adapted to the different spatial scales of deep-sea regions, while in areas with uniform bottom topography and isotropic currents, the array spacing could be varied to provide more resolution in horizontal wavenumber space.

Many of the sensors and techniques that require further development for the present application will also facilitate answering questions raised in the broader contexts of biodiversity in marine ecosystems, and the connections between biogeochemical cycling and climate. Finally, by taking measurements without major power and data storage constraints, we may expect to learn how to identify crucial variables in complex nonlinear interacting systems, and how to make significant estimates of such variables when power/storage constraints *are* present.

Science Box 4: Turbulent Mixing and Phytoplankton Community Structure

Phytoplankton provide the foundation of marine food webs in the upper ocean. Unlike their terrestrial cousins, marine plants lack both roots that could allow them to access deep pools of recycled nutrients, and branches that could position them favorably in the marine light field. Instead, surface layer phytoplankton are dependent upon turbulent motions to resupply them with nutrients and to move them, at least periodically, through light levels sufficient for growth (Figure 13).

Different species of phytoplankton have evolved to exploit different nutrient/light environments, as determined by the physical structure of the upper water column, itself a strong function of the strength of turbulent mixing. Broadly speaking, diatoms are characteristic of more strongly mixed regions, and flagellates are found in more highly stratified environments. However, phytoplankton species are highly opportunistic, and are able to increase rapidly whenever conditions become favorable. Thus, species composition in a particular area can change dramatically when nutrient and light conditions are affected by episodic, seasonal or decadal modulation of upper layer turbulence. Since such changes in community structure may be extended to global scales through interplay between the strength of turbulent mixing and the increased water column stratification that is a predicted result of global warming, it is essential to understand in detail how turbulence acts to determine the mix of phytoplankton species present at a given place and time.

The role of turbulence in development of a diatom-dominated versus dinoflagellate-dominated phytoplankton community is a classic textbook example of turbulence effects on upper-ocean ecosystems. But like most such examples, it is a simplified view of the system. Observatories provide a capability to look beyond the qualitative link between phytoplankton and turbulence to ask mechanistic questions such as:

(A) What are the consequences of a diatom-dominated (or dinoflagellate-dominated) phytoplankton community for regional primary productivity, the microbial loop and upper-ocean carbon cycling?

(B) If diatoms dominate surface phytoplankton populations instead of dinoflagellates, how does this condition propagate through the trophic web to impact fish stocks, marine mammals and carbon flux to the benthos? (This question incorporates concepts from the 'Ecosystem Dynamics' group)

Only with long-term observations and immediate sampling response to turbulence events will we be able to answer these questions and gain an ability to predict biophysical interactions.

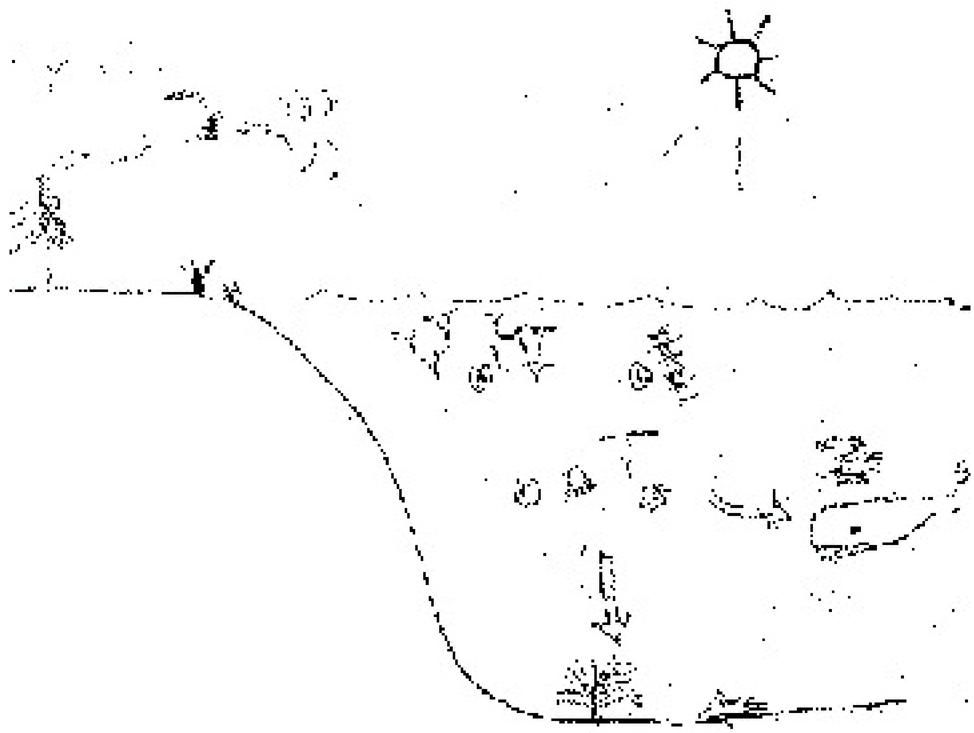


Figure 13. Potential trophic pathways of carbon from diatom and dinoflagellate blooms to the ocean and seafloor through microbes (e.g., in marine snow), zooplankton, and nekton. **(Please note: revised figure to be added by NSF)**

5. Ecosystem Dynamics

Introduction

Oceanographers have made impressive progress in understanding marine ecosystem dynamics - i.e., the changes in the distribution and abundance of marine species and their associated habitats - over the past 30 years. The next decade will see further advances in the areas of biodiversity, biogeochemical cycling, functional ecology, structure and distribution of biological assemblages and in understanding human impacts in these areas (*Ocean Sciences at the New Millennium* 2001). Within these topics are specific research questions that are particularly amenable to ecosystem time-series observations (*Illuminating the Hidden Planet* 2001):

- How do environmental and biotic factors influence species or communities (especially those important in biogeochemical cycles)?
- What are the functional dynamics of populations and communities?
- What are the dynamics of marine food webs?
- How can population and community changes be accurately forecast?
- What are the human impacts on marine ecosystems, and how can they be detected given the confounding effects of weather and climate change?

We know that ecosystems respond to environmental variation on time scales that correspond to daily, tidal, seasonal, and annual cycles, as well as to large-scale oceanic/atmospheric processes such as the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO). Ecosystems also vary in response to short-term episodic events including storms, upwelling events, turbidity flows, and seafloor volcanic eruptions. The biological responses (e.g., blooms, regime shifts) to these environmental perturbations are often difficult to predict in part because of the great disparity in species' generation times, which range from hours (microbes) to decades (large vertebrates) to centuries (deep-water corals). Furthermore, local ecosystems may be impacted by 'upstream' processes that link environmental and biological variation in one region to another (e.g., introduction of invasive species such as the *caulerpa taxifolia* and harmful algal bloom species). Observing these environmental changes, and quantifying ecosystem responses, requires a capability for reliable, sustained measurement and sampling, and is not accomplished easily using traditional ship-based oceanographic methods. Understanding and monitoring the response of marine systems to both local and remote dynamic forcing requires that we supplement ship-based observations with systems of continuously operating observatories.

Cabled observatories are needed for studies that require *in situ* instruments to relay real-time data for the identification and characterization of ecosystem responses to unpredictable environmental events. Cabled observatories are also needed for the deployment of long-term monitoring instruments with high power requirements and high data output. A cabled observatory provides the high-bandwidth data communication capabilities and high power supply needed for these sustained observations as well as two-way communication needed for adaptive sampling in response to events. The regional aspect is absolutely necessary for placing point-measurements and observed local responses in a larger oceanographic and geographic context.

The potential for anthropogenic effects and global climate change to alter the ocean in significant ways makes this a particularly important time for the study of marine ecosystem dynamics. For instance, introduction of contaminants may eliminate some populations, but enhance others by suppressing competitors or predators. Introduction of structures on the seafloor may alter benthic communities directly by altering flux of particulate food and indirectly by changing the sedimentary regime. Climate-related changes in water temperature and turbulence structure may have far-reaching effects as alterations in the character and production of phytoplankton propagate through the food web. A mechanistic understanding of ecological processes at the individual, population and community levels is needed to forecast the response of marine planktonic and benthic communities to oceanographic and climatic variability. Human activity has altered the composition and dynamics of marine communities in the past. We need an understanding of the biotic responses to natural variability if we hope to identify human impacts in the present and to predict how they will influence marine systems in the future.

Scientific themes that require cabled time series

The discussions of the Ecosystem Dynamics Working Group focused on an integrated research program to investigate responses of organisms, populations and communities to physical and chemical oceanographic drivers. Each of the topics below relates to the overarching theme of quantifying the response of pelagic and benthic ecosystems to variability in climate, upper ocean processes or tectonic/magmatic dynamics.

(1) Variation in pelagic ecosystems in response to upper ocean variation (e.g., storms, eddies, seasonality, ENSO)

Pelagic ecosystems may respond to changes in the upper ocean environment through several different mechanisms, including changes in individual behavior (vertical or horizontal migrations), physiological rates, feeding strategies and reproductive output, that result in altered population growth rates, species' geographical ranges and community structure. For instance, a shift in water mass distribution and circulation patterns may change an ecosystem directly through advection or mortality, or indirectly through trophic interactions between consumers and their prey. An increase in upper ocean turbulence may switch the balance between two different phytoplankton assemblages and propagate through the food web by altering the quality or quantity of zooplankton food resources for fish stocks, mammals and birds.

Currently we know very little about how ecologically and commercially important species respond to environmental variation, especially on long (multi-year) time scales or as episodic events. We need to understand how temperature mediates migration, how circulation influences larval drift and how turbulence affects predator efficiency in order to predict ecosystem response to a specific oceanographic change. Once we determine the mechanisms involved in ecosystem response to specific oceanographic drivers, we will have a capability to predict the potential effects of climate change and other large-scale phenomena. This capability is critical for informed management of fisheries stocks and endangered species.

(2) Variation in benthic or bentho-pelagic ecosystems in response to variation in the upper ocean.

Production from the upper ocean provides the organic carbon for most of the organisms (megafauna, macrofauna and microbes) living on or near the deep seafloor.

The distribution and abundance of an individual species may change in response to upper ocean variation, depending on its life-history, feeding mode and interactions with other species. It is particularly important to determine the influence of upper ocean variability, including episodic events, on species that exert a large effect in the community through their high abundance, influence on carbon flow or critical role in the food web. For these species, investigating rates of reproduction, growth, and survival, as well as interactions with other species, will help determine their subsequent influence on the community. Examples of metazoans and microbes with a disproportionately strong effect on biogeochemical transformations include species or groups contributing greatly to productivity in the upper ocean, and those responsible for the majority of organic carbon remineralization in the water column and at the seafloor. Furthermore, recruitment of many benthic species from the pelagic environment is closely linked to episodic events in the water column such as upwelling and phytoplankton blooms. In summary, the physico-chemical variability driven by climate and upper-ocean processes affects deep-dwelling organisms both directly by affecting food supply and dispersal stages, and indirectly by influencing the abundance, behavior or metabolism of other species with which they interact. The strength of this coupling between pelagic and benthic systems is expected to vary depending on location and oceanographic regime.

(3) Variation in benthic and pelagic ecosystems in response to seafloor hydrothermal activity

The hydrothermal fluids associated with volcanism at mid-ocean ridges, in intraplate settings and along convergent margins support a variety of life-forms, from thermophilic bacteria in the subsurface to megafauna on the seafloor around vents. These ecosystems are tightly linked to geological, physical and chemical features of their environment. Understanding the nature of these links, and their variation in response to transient events, such as episodic dike intrusions and volcanic eruptions, will lead to insight into how these unique communities maintain themselves in this harsh and highly variable environment. Temporal development and succession in these communities is particularly intriguing because major environmental perturbations occur on time scales similar to the metazoans' life spans. Just as environmental variation in the upper ocean may result in distinct changes in the seafloor benthos, events on the seafloor may substantially affect the chemistry and ecology of the overlying water column, as well as remote vent ecosystems. This influence is transferred via the hydrothermal plume in the form of chemicals, nutrients, mineral and organic particles, microbes, and larvae.

Seafloor seeps in the continental margins support benthic communities that are analogous to those at hydrothermal vents. However, they typically are sedimented, providing a three-dimensionality to the ecosystem that supports microbial life in the subsurface, and exposes microbes and other infauna to sulfate reduction gradients. The dynamics of populations and communities at seeps provides an interesting contrast to the more familiar hydrothermal-vent and shallow-water systems.

Rationale for cabled system

Four of the greatest limitations to any underwater monitoring program (i.e. not just photographic) to date have been (1) the longevity of battery power for instrumentation, (2) data storage, (3) the inability to collect/analyze data and alter sampling frequencies in real time, and (4) the inability to correct or compensate for malfunctions in real time.

Given the large temporal variations recently discovered in particulate organic matter fluxes (as an indication of food supply) to several areas of the deep ocean, it is critical to expand time-series measurements in the deep sea. Long time-series measurements of both food supply and activity of deep-sea organisms are critical to any informed decisions regarding the health, longevity, and resilience of deep-sea communities.

Although some of the sampling activities associated with the above studies could be accomplished without a cable, most of the studies require high bandwidth, high power, or both. In particular, studies of rate processes, larval dynamics, production, carbon cycling, succession, and behavior of large mammals and fish require both the cable and the spatial coverage of a regional cabled observatory.

Studies of recruitment and ecosystem change in response to disturbance are difficult to address with "snapshot" science, where time trajectories are based on one or two data points along a continuum of change. This issue has plagued cruise-based ecological studies since they began in the last century, and can only be resolved through high intensity observation. For surface processes, satellite imagery has revolutionized oceanography, but for subsurface processes this imagery is not sufficient, and major advances will only be achieved through the continuous observation such as that possible with cabled observatories.

Our capacity to manage wild fisheries is compromised by our limited temporal and spatial coverage of the ocean environment, and the seasonal movements of fish and their different life history stages. Megafaunal taxa such as surfclams and groundfish are typically managed based on catch data and modest amounts of independent sample collections that are typically done at only a few times a year at best. Recruitment is typically only determined once individuals are large enough to actually enter the fishery, and information on their dynamics until that time are woefully inadequate

Phytodetritus sedimentation events in the ocean are tremendously important to benthic living organisms but they are also very important in carbon and nutrient cycling. These events are notoriously unpredictable and relate to warming rates, ice breakup, spring mixing dynamics, mesoscale eddies and fronts, and other processes that vary in space and time. This variability makes it extremely difficult to capture these events with shipboard sampling that is constrained in timing and location.

Succession events on the seafloor are often related to events such as slumping and storms that are episodic in nature. The timing of these events may or may not coincide with larval pulses that may influence recruitment success and failure, and once again these events are often impossible to predict. Monitoring vent ecosystems at relevant time scales (years to decades) and responding to unpredictable eruptive events requires the power, data and communications capabilities of a cabled observatory system.

Sampling strategies and sensors for cabled time series of ecosystem dynamics

A cabled system will allow integrated studies of ecosystem composition and population dynamics of the important species as well as energy flow through the system. It will also facilitate linkage of ecosystem studies with other disciplinary measurements (fluid flow, coastal processes, physical oceanography, etc). The multitude of sensors and integration of various ecosystem measures requires a high power, high bandwidth system available for extended periods spanning important ocean cycles (seasonal, ENSO, PDO, NAO) and episodic events.

Many of the ecosystems studies will require monitoring of the species composition and abundance of benthic and pelagic habitats. The measuring and sampling techniques differ depending on the size-class of the organism. Megafauna (which are observable in seafloor photos) can be quantified with optical systems (camera tripods, surveying AUVs) and acoustic systems, both active (ADCPs) and passive (acoustic tags in fish). Macrofauna (smaller animals) can be measured with an optical plankton counter or video systems for water column species, and a microscopic camera for sediment dwellers. Instruments need to be developed for sampling and preservation of organisms for later analyses. Meiofauna (tiny 'bugs') can be sampled with a sediment sampler and preservation system, and in the future will be characterized by an *in situ* DNA probe system for species identification. Microbial communities also can be collected in sediment samples and preserved for later analyses, or collected in a sediment trap or water column collector. In the future they will be analyzed with an *in situ* instrument for genetic identification of known species.

Sampling for species composition and abundance will detect changes in population abundance, but other responses (e.g., behavioral, reproductive) will require other measures. For megafauna, changes in behavior may be detected via acoustic tracking. However, instrument development will be necessary to collect samples for other analyses. For macrofauna, sample collection and preservation systems are needed to provide samples for analyses of reproductive or physiological conditions that vary in response to carbon input. Optical systems and other detectors (e.g., *in situ* genetic analyzers) may allow detection of spawning or settlement events for some species. For meiofauna and microbes, similar systems for sample collection, *in situ* molecular genetic analysis and preservation are needed.

For carbon flux studies, the intent is to determine the rates of food input to the benthic boundary layer and its variation in quantity and quality through time. Flux rate is measured with sediment traps, which can quantify the amount of material over time, but not characterize it. Advanced (to be developed) trap systems may provide some characterization of flux using optical techniques. An *in situ* mass spectrometer / Carbon-Hydrogen-Nitrogen (CHN) analyzer may be developed to allow additional characterization. Optical instruments will be used to quantify and categorize biological particles. Quantifying sediment community metabolic rates requires Sediment Carbon Oxygen Concentration (SCOC) measurements using a mobile benthic respiration system (e.g., a benthic rover), and a microbial sample processor to measure microbial uptake rates of CO_2.

Deep-sea studies will rely on collaborating research groups to evaluate the production and export of material from the euphotic zone and its response to atmospheric and hydrographic forcing. Shallow water studies will allow more complete characterization of the water column.

Sensor Systems

Optical and acoustic systems that are currently available for imaging and quantifying particles and organisms in observatory mode include fluorometers, acoustic backscatter systems (for sediment concentration), spectral absorption, scattering and attenuation meters, transmissometers, nephelometers, flow-cytometers, optical plankton counters, video plankton recorders, and video and holographic cameras. Acoustic imaging also is in use for identifying and quantifying organisms both in the water column and sediments. *In situ* analyzers have been developed for nitrate and other nutrients, iron and other metals, and sulfide (e.g., some using spectrophotometric method). Species identification can be accomplished for target algal species using an Environmental Sample Processor (ESP) that collects and analyzes organisms *in situ*. This technology is under development for larvae and microbes. Organisms can be collected and preserved in sediment traps (conventional and newly-developed to assess quality and quantity of flux), pump systems, and on settlement panels. Technological developments, however, are needed for long-term freezing or chemical preservation and storage of samples. *In situ* chambers that measure microbial metabolic rates also are in use, and could be further developed for a wider range of measurements and longer time-series operation. Behavior and movement of larger organisms (i.e., fish and marine mammals) can be tracked with moored acoustic receivers that monitor their natural sounds and/or signals from acoustic transmitters (Chat tags). Most of these systems will be used from a fixed position, but many also can be used on mobile vehicles such as AUVs and benthic rovers. They will be used in concert with traditional oceanographic gear, such as current meters and CTDs, and the studies will benefit from the diverse environmental measurements gathered by the observatory.

Many of these instruments have especially high power requirements (e.g., freezers, *in situ* microbial genetic processors, lights for video systems), or high data acquisition rates (acoustic and optical particle analyzers). These and others (e.g., particle traps, pumps, nutrient and metal sensors) require two-way communications to modify sampling strategies in response to events. These collective requirements can be best met by cabled observatories.

Locations and Priorities

A variety of habitat types will be needed to provide suitable geographic and oceanographic settings for the diverse ecosystem dynamics questions listed above. Questions 1 and 2 can be addressed in coastal (as described in earlier section), continental-shelf, or deep-ocean regions. Continental shelf regions are good candidates because they are highly productive, have high rates of nutrient cycling, and are host to the vast majority of commercially important species. Alternatively, deep-sea regions are likely to be sites where novel discoveries are made because the ecosystem has not been accessible to traditional oceanographic investigation. For instance, Question 1 would be appropriate for a deep basin underlying a dynamic frontal region between an upwelling and downwelling gyre, and Question 2 is appropriate for a deep-sea region in close proximity to a productive shelf area. Question 3 requires a deep hydrothermal system and a marginal cold-seep system, each inhabited by unique chemosynthetic communities. Although direct applications of vent and seep research are less obvious than in some other (e.g., fisheries-related) habitats, these studies investigate fundamental questions about species diversity and adaptations in ocean habitats. A carefully located regional observatory could accommodate many of these types of studies, provided it spans coastal to deep waters, and has nodes at active hydrothermal and seep environments. However, a single observatory is unlikely to support all the themes described herein and limits comparative studies between different oceanographic settings. Thus, multiple regional observatories will be needed for a comprehensive understanding of marine ecosystem dynamical responses, particularly to large-scale phenomena such as climate change. For some research questions, extending an existing observatory system may be the most efficient and economical way to initiate observatory studies in a specific location.

Synergies

Ecosystem dynamics are a component of several other research topics addressed in the context of a regional cabled observatory. This group concentrated on processes occurring from the continental shelf to the abyssal deep-sea, but many of the research questions and measurement strategies apply to coastal systems. Similarly, the issues of biological/physical interactions addressed by the Turbulence group are complementary to the topics of pelagic/benthic coupling and effects of surface phenomena on pelagic and benthic communities. Carbon cycling is mediated by many of the ecosystems described in this section, and the dynamics of hydrothermal vent and seep communities clearly are associated with the processes described in the Seafloor Fluids group. Furthermore, the dynamics of deep-sea hydrothermal vent ecosystems are linked directly to geophysical events that perturb the fluid and life-support system of their inhabitants. Monitoring of such geophysical events is described as part of the Geophysics section.

Studies of ecosystem dynamics via a cabled observatory system have clear and direct applications to the health of marine fisheries, sustainable use of coastal ecosystems, and prediction of environmental effects of future human activity. Time series observation systems are one of the only suitable methods of quantifying the dynamics in highly variable environments, especially those with unpredictable, episodic events. It is advisable to place these systems in coastal and shelf locations where physical/chemical dynamics are variable, episodic events frequent, productivity and remineralization rates high, water column-benthic coupling strong, and where the majority of the commercially-exploited populations live. It is also advisable to place systems in deep waters, where novel discoveries are likely, dynamics occur on different time scales, and unique ecosystems are driven by a complex interplay of deep-earth dynamics and surface seasonality.

Figure 14. Deep-sea holothurian with its feeding tentacles atop a patch of phytodetritus, central North Pacific.

Science Box 5: Studies of human effects – observational and manipulative

The cabled seafloor observatory provides an opportunity for observation of, and manipulative experimentation on, the effects of human activities on benthic ecosystems. It provides a platform for observing effects of human activities, both extrinsic and directly related to the observatory, and an opportunity to test procedures for mitigating them.

The presence of an observatory node provides an experimental manipulation in that it alters fine-scale flows that are known to influence patterns of recruitment and species composition. Moreover, observations of episodic slumping events and experimental studies of sludge dumping and manganese nodule mining simulations suggest that resuspension processes have dramatic consequences for benthic organisms and seabed geochemistry. The disturbance of laying the cable itself therefore creates an experimental manipulation relating to disturbance response of benthic organisms and associated changes in sedimentary geochemistry. The research activities associated with the observatory such as sediment sampling and repeated collection of organisms are likely to impact local population dynamics. Manipulations other than those caused by normal observatory operations also can be conducted, such as experimental injections of CO_2 into seafloor sediments.

Figure 15. Interactions between instruments deployed on the ocean floor and the local ecosystem were monitored at a cabled observatory using a pan/tilt/zoom video camera controlled from shore. In this image, a bottom boundary layer tripod equipped with Benthic Acoustic Stress Sensors (BASS) is shown to attract numerous fish that disrupt the physical measurements during low flow conditions. As wave orbital velocities and currents increase, the fish tend to scatter, and undisturbed flow measurements are obtained.

6. Ocean, Climate, and Biogeochemical Cycling

Introduction

The ocean is an intrinsic component of Earth's climate system and will play a central role in modulating climate change. Given potential human-induced changes in global biogeochemical cycles (e.g., carbon, nitrogen, etc.), research efforts will necessarily focus on elemental cycling between land, atmosphere, ocean, and lithosphere. For example, understanding how climate change 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.

The ocean is currently estimated to be a sink for anthropogenic carbon, taking up about 30% of the carbon released by human activity. Several studies are currently underway and planned to quantify the oceanic CO_2 sink on the global scale. Long-term measurements of physical and biogeochemical phenomena are perhaps some of the most valuable data for understanding how the physical and biogeochemical system functions and changes over time. These observations are also critical to determine whether changes are due to naturally occurring processes or are caused by man's intervention.

One of the most important and well-known "global change" studies is the time series program for obtaining atmospheric CO_2 data initiated by Keeling in 1958 at the Mauna Loa Observatory in Hawaii. Also, the broader scale fishery and climatic events in the Pacific Ocean would have been difficult, if not impossible, to describe without the long-term measurements of the "Southern Oscillation" index, pressure difference between Darwin and Tahiti. Oceanographic time series for physical and biogeochemical as well as ecosystem variability have been conducted off Hawaii (Hawaii Ocean Time-series; HOTs) and off Bermuda (Bermuda Atlantic Time-series Study; BATS) since 1988. These programs are documenting major changes in ecosystem structures and increasing dissolved inorganic carbon concentrations in the upper ocean. Both programs have relied upon ship-based and mooring platform data sets. Few *in situ* data have been collected for determination of horizontal spatial variability - primarily because of the lack of technologies and resources. Further, satellites are being used to infer mesoscale variability; however, satellite measurements are confined to surface properties and thus blind to important subsurface structures and frequently obviated because of cloud conditions (for temperature and color). Thus, conclusions based solely on remote sensing data are likely flawed.

Examples of Climate and Biogeochemical Questions

There are several climate and biogeochemical questions that can benefit substantially by use of the cable observatory approach. Two open ocean examples are presented below and a coastal example is summarized in Science Box 6:

(1) What role do mesoscale eddies and episodic wind events play in biogeochemical cycling and carbon fluxes to the deep-sea?

Regional processes, which occur irregularly on subseasonal to decadal time scales with complex spatial structures, have been hypothesized to have profound effects on ocean biogeochemistry and on the net balance of carbon between the atmosphere and the ocean. Furthermore, many of the changes occurring on the regional scale are connected to the global scale changes through ecosystem dynamics and rates. For example, the production, consumption and burial of carbon and associated bioelements in the deep-sea are largely dependent upon the activities of marine organisms ranging from bacteria to fish. Cycling of key nutrient elements (e.g., N and P) is linked to the marine biota, especially microorganisms. Understanding this elemental cycling has been the focus of much of the oceanographic community (e.g., JGOFS).

Some examples from the past few years included observational and modeling studies that have investigated and attempted to quantify the contributions that open ocean mesoscale eddies make to primary production, new production, and nutrient and carbon budgets and fluxes. A smaller number have also considered the effects of carbon dioxide fluxes across the air-sea interface in response to intense storms including hurricanes. In addition, episodic inputs of atmospheric terrigenous iron at the ocean surface may be important as well. Despite the results of these scientifically well-conceived and well-executed studies, our understanding is incomplete. This is largely because of inadequate 3-dimensional and temporal sampling and modeling of the upper ocean. In particular, it has not been technologically possible to synoptically measure or model biogeochemical and physical processes that span time and space scales relevant to the problem (i.e., minutes to months and meters or less to a few hundred kilometers). Existing observational capabilities fail to adequately resolve (temporally, spatially, and spectrally) these processes. Similarly, regional processes are not adequately resolved in the current state-of-the-art ocean models used to study the response of carbon cycling to the increased atmospheric CO_2. Long-term, high spatial and temporal resolution data are required to characterize these regional processes and their potential impacts on the ecosystem and carbon fluxes.

(2) How do interannual variability and global climate affect regional biogeochemical processes and budgets?

The oceans and atmosphere exhibit significant natural fluctuations on the interannual to interdecadal time scales as well as longer term climate scales in addition to lesser understood anthopogenecally-induced variability. For example, well-known, large-scale climatic phenomena include El Niño/La Niña (Southern Oscillation or ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO). These phenomena likely significantly influence regional ocean circulation and associated biogeochemical and fishery variations. Some regions of the ocean are immediately influenced by these lower frequency phenomena; however, other parts of the ocean can experience a delayed response. For example, the U.S. west coast experiences the impact of El Niño generated near the equatorial Pacific with a time delay from weeks to months (via Kelvin waves and atmospheric teleconnections). The changing physical conditions associated with El Niño and PDO are hypothesized to also cause longer time scale phenomena such as major collapses and recoveries of fisheries off the U.S. west coast.

Presently, our sparse ocean observing network consists of limited numbers of single point measurement systems at selected locations, modest numbers of drifters and floats, periodic or occasional ship surveys along particular transect lines, satellite surface observations, and occasional field experiments in limited region. Additionally, these platforms presently carry few sensors relevant to biogeochemical processes. It is thus difficult, if not impossible, to use these aliased observations to describe and understand these interannual-to-interdecadal variabilities. Regional cabled observatories either in or spanning selected coastal and open ocean areas would be ideal laboratories to provide the long-term, high spatial and temporal resolution, coherent interdisciplinary data sets needed to characterize a broad spectrum of regional processes (including both open-ocean mesoscale eddies and coastal upwelling) and their potential impact on the ecosystem and carbon cycling.

Studying Climate and Biogeochemical Cycling

The ocean's impact on climate has been studied primarily on the global scale. The successful study and modeling of biogeochemical and specifically carbon cycling and fishery distributions and variabilities require adequate spatial/temporal coverage. Presently, large-scale models generally attempt to simulate global climate change and biogeochemical variability using horizontal grid size on the order of 100 km or more and thus cannot resolve processes such as fronts, submesoscale features, and mesoscale eddies. Again, there are several studies suggesting that these are important processes and that they require horizontal spatial resolution on the order of a few kilometers or less. To quantify the contributions of carbon cycling on these regional scales to the global carbon budget thus requires a new generation of ocean observation tools and ocean models that adequately resolve and encompass both the small-scale regional and the large-scale global processes. It is anticipated that cabled observatories, implemented over carefully selected regions, could provide a new data stream to improve our capability of understanding and modeling the carbon cycling within these regional oceans and their potential coherence and subsequent interactions with the global ocean.

It is useful to consider a specific open ocean example to illustrate the potential impact and value of cable technologies. Consider an open ocean time series program designed for biogeochemical cycling and climate studies. Suppose that the program's interdisciplinary time series observations are obtained from ships at monthly intervals and from moorings at minute to hourly sampling intervals. This program can in principle resolve local biogeochemical and physical processes of relevance to the biogeochemical- and climate-related questions described above. However, horizontal variability will be unknown and the contributions of advective processes, which may be substantial, will be unquantified. Some spatial contextual information could be inferred from satellite-derived data sets or occasional ship transect sampling or passages of profiling floats, drifters or gliders -most of which would likely lack requisite interdisciplinary sensor suites. Thus, the two questions above remain unanswered largely because of the lack of synoptic, coherent, interdisciplinary, high frequency, fully 3-dimensional spatial data to resolve scales from meters to the order of 100's km. Importantly, model simulations and predictions cannot be expected to be valid until the observational databases are adequately developed. Here we suggest that cable systems can greatly improve our biogeochemical and climate observational databases by providing 1) the means to support (through power supply and data links) a limited array of moorings (and bottom tripods) to infer and quantify advective features and contributions at the submesoscale, 2) provide power for mobile platforms including gliders and propeller-driven AUVs, and 3) specifically, powering of interdisciplinary sensors and systems (especially those with high power demand) and enabling greater data transmission bandwidth for high frequency sampling of high spectral resolution optical (and video) and multi-frequency acoustical instrumentation. The net effect of adding the cabled component (including mobile sampling assets) to the existing sampling assets would be to effectively increase the number of relevant biogeochemical and physical variables and provide information on time scales from minutes to years and space scales from meters or less to a few hundred kilometers. Again, modeling, especially data assimilation modeling, will be critical to provide information to help span the informational time-space continuum and the data sets will be vital for model parameter estimation, formulations, and validation tests. These same points generally apply to coastal biogeochemical and climate sampling scenarios such as the one outlined in Science Box 6.

Sampling Strategy and Sensors/Systems

For cabled observatory systems to provide infrastructure relevant to water column elemental cycling (see above), scientific nodes (including their mobile platform assets) must have horizontal spacing that can resolve the relevant processes. For example, many of the questions addressed here require data on scales of order 10 km or less. More precise estimates of requisite node spacing and mobile platform sampling will need to be determined from a combination of high resolution pilot studies and Observing System Simulation Experiments (OSSEs). While OSSEs with physical models are more common, it is recognized that coupled multi-disciplinary OSSEs will be highly model dependent, since different chemical, biological or geological models may still not have sufficiently converged for the OSSEs to be useful. Thus there is still a need for oversampling in the spatial domain to provide the scientific datasets required to improve the coupled models so that OSSEs can provide useful feedback to spatial sampling questions. Given this scientific need, a major concern is how best to implement the cabled observatory systems which will not ignore the spatial sampling constraints. Cabled observatories for biogeochemical and climate studies could be implemented in phases.

- The first phase could involve enhancing existing and emerging time series programs and cabled observatories to serve as testbed cabled observatories. These pilot/testbed efforts could be used to demonstrate various technology components, gain operational experiences, learn how to put together the science experiments, and conduct education and public outreach activities.
- The second phase could involve the phased development of regional cabled observatories using several primary nodes complemented with secondary junction boxes in order to improve spatial coverage with additional fixed-location and mobile assets.
- The third phase could link various regional cabled observatories and establish permanent cabled observatory networks along the entire U.S. coastline.
- The fourth phase could extend the regional cabled observatories from the U.S. coastlines into the open ocean.
- A fifth phase could entail utilization of cabled system in especially adverse environments such as the Arctic and Southern Ocean regions. For example, global change is expected to initially impact polar regions most dramatically.

Through this phased approach, we would gradually learn how to better understand the science problems and answer science questions that can be best addressed with cabled observatories. Once observations become routine and their interpretations better understood, the science demonstration could be translated into an operational facility. The operational component of proposed cabled observatories should be sustained in analogy to weather observing systems or sea level measurement networks.

Sensor and system design should involve scientists from a variety of disciplines including physics, chemistry, biology, ecology, geology, and fisheries. Cabled observatories would provide unprecedented power and data transmission for multi-disciplinary studies. Careful site selection is crucial if future data sets are to be useful for regional extrapolations and predictions of change. OSSEs will be important tools to characterize and refine the attributes of a particular cabled observatory. The cabled observatory approach should capitalize on an adaptive sampling capability for approaching key scientific objectives such as system responses to event-like forcing. Adaptive sampling issues to be discussed include quality-controlling data in real-time to provide alerts to human decision makers or triggers for predetermined sampling programs, and the need to avoid compromising core time series during such contingency sampling.

Another key requirement for the implementation of cabled observatories is the real-time data transfer from the sensors/systems to data archival and distribution centers, and more importantly to the end users. This requires the best technology for data transfer, data access/mining, and data analyses and visualizations. The real-time capability is required for scientific investigations (e.g., predictions) as well as education and public outreach.

Some of the key variables/parameters, which are relevant to climate and biogeochemical cycling, and can in principle be measured using cabled observatories are listed in Table 2 according to discipline.

Table 2. Key variables/parameters for climate and biogeochemical cycling

- Physics:
  - air-sea fluxes (momentum and net heat fluxes including spectral surface irradiance, latent heat, sensible heat, and fresh-water),
  - temperature, salinity, and currents,
  - bottom pressure,
  - transport,
  - turbulence,
  - heat content;
- Chemistry:
  - salinity
  - nutrients (N, P, Si),
  - Fe and other trace elements,
  - O_2, CO_2, pCO_2,
  - pH,
  - DOM;
- Biology:
  - phytoplankton,
  - zooplankton,
  - microbial community (both water-column and benthic);
- Bio-optics:
  - spectral or hyperspectral inherent and apparent optical properties (IOPs and AOPs).
  - Chlorophyll fluorescence.
  - CDOM

Existing platforms/systems include:

- fixed-depth and profiling moored systems,
- surface drifters,
- profiling floats,

- acoustic Doppler current profiler (ADCP),
- bottom pressure gauge,
- autonomous underwater vehicles (AUVs) and gliders
- integrated acoustics systems (e.g., inverted echo sounder, tomography, wind, rain, navigation, and communications),
- electrometer for barotropic velocity measurements.

There are a number of areas that require special technological development:

- chemical and biological sensors,
- population biological sensors and systems (e.g., acoustic technology),
- bio-optical sensors.

Synergy

Long-term time series studies are ideally suited for investigation of subtle habitat changes, irregularly spaced stochastic events and complex interdependent physical, biogeochemical and ecological phenomena that affect global elemental cycles in the world ocean. Regional cabled observatories should be implemented synergistically with the other two components of the OOI, i.e., deep-sea buoys and coastal observing networks.

This synergistic theme is well reflected in studies of the carbon cycling problem. Currently, one of the largest unknowns in the global carbon cycle is the carbon flux from small-scale regional processes including both open-ocean mesoscale eddies and coastal upwelling. We will not be able to close the carbon budget until we can quantify the roles of eddies and coastal oceans in carbon fluxes and budgets (Science Box 6). The same is true for nitrogen, sulfur, and other trace elements. Regional cabled observatories would provide continuous sampling from the shelf to the deep sea, thus providing a natural link between the coastal observing network on the shelf and the global-scale climate monitoring network.

Regional cabled observatories with an improved spatial coverage could also complement the current open ocean time series programs like HOT, BATS and other nascent international time series programs. They also provide an improved database for satellite calibration activities. Currently, the existing calibration/validation activities for satellite observations are mostly based on a few-point calibration sites (e.g., off Hawaii and Bermuda), while satellites usually measure over kilometer-scale footprints. With the cabled observatory approach, one can sustain a network of moorings and autonomous underwater vehicles to provide improved spatial sampling, so that more direct comparisons can be made between *in situ* and satellite observations.

Numerical modeling and data assimilation should also be included in the design and implementation of regional cabled observatories. Before the implementation of cabled observatories, 3-dimensional computer models (particularly coupled models linking various physical and biogeochemical processes) can be used to quantify the science requirements (e.g., the spatial scale and sampling frequency) and to conduct tradeoff (OSSE) studies comparing the effectiveness of various observing scenarios. After the implementation of cabled observatories, the real-time data can contribute to the larger set of data being assimilated into these models to perform predictions, thus translating scientific data into specific products for end-users.

Science Box 6: Monitoring Carbon Cycling in the Coastal Ocean with Cabled Observational Networks

The coastal oceans, despite occupying only 10% of the global ocean, are sites of substantial carbon uptake through marine photosynthesis, resulting in possibly significant, though still highly uncertain, exchange and transport of carbon to the deep sea (i.e., export production). In particular, it is still unclear whether continental shelves are net sources or sinks of carbon. Additionally, we do not know the spatial and temporal scales of exchange and transport. A fundamental need is to be able to identify and quantify the sources, and sinks of key biogeochemical variables along with their transport and transformations. The processes relevant to the biogeochemistry of the coastal ocean generally include those mentioned earlier for the open ocean. However, some additional processes and effects are additionally important for the coastal setting. These include: tides, riverine and storm runoff of fresh waters, buoyancy driven flows, topographic effects, shelf waves, upwelling, jets, meanders, fronts, internal waves, bottom boundary layers and sediment resuspension. Further, there is considerably more complexity because of greater species diversity (including harmful algae and invasive species), a larger number of important chemical variables (i.e., pollutants), and additional optically important constituents (e.g., colored dissolved organic matter, CDOM; suspended sediments and detrital matter). Also, time and space scales of physical and biogeochemical variability are typically even smaller in the coastal domain and also remain undersampled and under-resolved by observational systems and models at present. Given these challenges, a central scientific problem for the coastal ocean problem is to quantify how regional changes in biogeochemistry are driven by local (e.g., local upwelling) or global (e.g., ENSO) processes. Considering the difficulty in documenting coastal dynamics and the need to provide a large scale picture of elemental dynamics on the continental shelves, a spatial grid of cabled observatories, placed within the well-sampled ocean of the future (IOOS), could provide coherent data fidelity for this science problem. A conceptual diagram showing a hypothetical cabled system that encompasses biogeochemical and physical measurements along the east coast of the United States is provided in Science Box 5 (see Figure 16).

The previous open ocean discussion of sampling design, sensors and systems applies here as well. Again, it should be emphasized that multiple platforms, stationary and mobile, equipped with broad suites of interdisciplinary sensor will be necessary and used in concert with models to enhance spectral coverage in space and time and to enable prediction. Also, OSSEs will be needed for experimental design. Among the many science problems/questions that can be best addressed by the cabled observatory approach, carbon cycling in the coastal ocean is one of the common science themes cutting across several of the other science sections. The synergetic view of carbon cycling linking all the science of these other foci is illustrated in Figure 16.

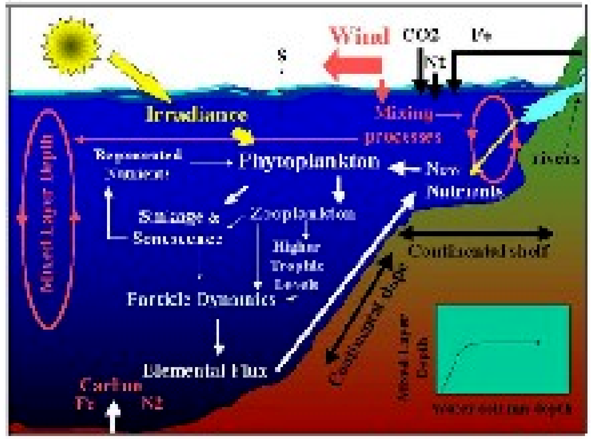


Figure 16. A schematic illustrating some of the processes that influence biogeochemical cycles. Destratification of shallow ocean ecosystems requires less meteorological forcing than the deep ocean. This destratification allows mixing of nutrient rich waters into the euphotic zone. This results in higher biogeochemical rates on continental shelves. This relationship between mixed layer depth and water column depth is illustrated in the corner inset.

Figure 17. A hypothetical regional cabled observatory designed to study biogeochemical cycles across the continental shelf into deep water. This regional observatory could unite the numerous IOOS Coastal Observatories (denoted by red dots).

7. Technology to Support Regional Scale Cabled Observatories

Ocean observatories should form the basis of a coherent sensing array for interdisciplinary variables that need to be sampled concurrently on a range of time and space scales commensurate with the relevant oceanic processes as described in earlier sections. As indicated above, a variety of platforms and sampling strategies will be required. Specific sensors and systems were described and discussed in the relevant science sections. It will be imperative in the implementation phase to interface these sensors and systems to the mobile and stationary platforms and the backbone cable infrastructure. Some of the major elements that will comprise a cabled observatory and supporting sampling platforms are described below.

Cabled observatories will use modern telecommunications cables to support a network of sensors and instruments on and beneath the seafloor, and in the water column. A system should be capable of employing several thousand kilometers of cable. While the technologies and methods developed by the subsea telecommunications industry provide a strong foundation, designing and implementing a cabled observatory will have unique technical challenges.

The cabled infrastructure provides a level of power and communications connectivity to the ocean interior unmatched by any other technology. Using existing multi-fiber subsea cables, and/or multiple wavelengths of light on each fiber pair, existing Gigabit Ethernet will enable communication capacities of order 10 Gbps (Gigabits per second). This bandwidth has been considered so great that emphasis has been given to off-the-shelf solutions. To place this data rate in perspective, it is equivalent to over 525 High Definition Televison (HDTV) channels and would generate over 150,000 CDs per day. By way of comparison, the entire Iridium satellite system has a capacity of 190 Mbps. The GlobalStar system can achieve 553 Mbps. By the time the regional cabled observatories are deployed, 10 Gigabit Ethernet may have matured sufficiently to be employed subsea, in which case the total capacity would be on the order of 100 Gbps. Although Gigabyte Ethernet is considered a baseline, other communication protocols are being introduced by the cable industry, and should be considered.

A single shore-based station should be able to provide up to 100 kW to a subsea observatory, enough to supply the electrical needs of 86 average American households. This is more power than is transmitted through present subsea telecommunication systems, but nonetheless within the electrical capabilities of existing cables. While there will be transmission losses and other inefficiencies, peak power delivery to subsea scientific nodes should be on the order of 10 kW. While the power levels are well within the theoretical, but operationally untested, capability of existing cables, many characteristics of this system have more similarity to the land power grid than a traditional submarine cable system. The system must be able to maintain high quality electrical power at all the nodes in the face of unpredictable variations in demand. Furthermore, the power system must be highly robust and minimally susceptible to the wide range of possible failures, ranging from problems with attached instruments and connectors to damage to the cable infrastructure itself.

The physical elements of a regional cabled observatory facility include: a cable, a shore station, branching units, and instrumented science nodes (see Figure 1). These elements function together to provide:

(1) A power distribution system
(2) A communication network for data transfer, command and control, and accurate time delivery, and
(3) Locations for standard sensor suites as well as short-term experiment specific sensors.

Important elements beyond the cable infrastructure include data management and archiving, community instruments and tools, supporting vessels and remotely operated vehicles (ROVs), and observatory staff.

The 'generic' cabled observatory depicted in Figure 1 shows a number of the critical features that will characterize next-generation cabled observatories. The number of shore landings (where the cable crosses from the sea to the shore) will likely be kept to a minimum because of the high cost of permitting and installing cables 'across the beach.' However, a regional cabled observatory will unlikely be able to rely on just one shore landing. Multiple shore landings mean more opportunities to deliver higher power offshore, so cost tradeoffs should be evaluated. Since the shallow portions of the system are likely to be at greater risk of breakage than the deeper portions, redundancy in access to a deep-sea network is attractive. Elements of the cable on the continental shelf are likely to be buried for protection from human activity, but as with existing cables, can remain accessible by surfacing within protective nodes; deeper portions of the cable can be left on top of the seafloor.

Subsea fiber-optic cables require repeater nodes spaced less than about 100 kilometers apart to overcome optical attenuation. For cabled observatories, repeaters may serve a dual function of both signal amplification and subsea breakouts from the main cable to allow subsea junctions. The junctions may be used to create cable spurs or to directly support science. The ability to modify the geographic coverage of the observatory will likely be very important, consequently the flexibility to extend the main cable or add smaller spur cables, perhaps at pre-planned locations, for scientific nodes will be desirable for regional cabled observatories.

Technological Foundation

The technological base for building, installing, and maintaining seafloor cables has been developed by the telecommunications industry. Subsea telecommunication cables have a long history with over 300,000 km of subsea cable installed by 1997. The first successful trans-Atlantic cable was laid in the 1860s, and supported communications rates of a few bits per second. While tremendous advances were made over the subsequent century, the era of modern subsea cables was ushered in by the installation of the first fiber-optic cable across the Atlantic, TAT-8 in 1988. This cable provided an effective capacity of nearly 1 Gbps.

Although the first fiber-optic cables provided a tremendous improvement over the prior generation of coaxial cables, even greater leaps were made in the subsequent two decades (see Figure 18). The most recent generation of subsea cables employs multiple fibers in cables less than an inch in diameter and provides capacities in excess of a Terabit per second. Regional cabled observatories will use the same fiber-optic technology, but different communications protocols to support subsea networking, and thus will operate with lower communication capacities.

Reliability is extremely important for the telecommunications industry given the large revenue loss for downtime. Failures can stem from equipment faults, poor deployment practice, operator error, natural events, or human activity. Achieving high reliability has been a very heavy emphasis for subsea cable development. So effective have those efforts been that cables installed several decades ago are still functional. For example, the Hawaii 2 Observatory uses the Hawaii 2 AT&T cable installed in 1974. Good seafloor maps are considered a prerequisite for safe deployment of subsea cables. Significant seafloor topography can cause cables to be suspended off the bottom, in effect 'draped' between features. The suspended cable will have a very high drag in near-bottom currents. Vortex-shedding induced strumming is highly likely, and can lead to cable failure. Where seafloor topography is unavoidable, part of the deployment problem, solved decades ago, is to ensure that the cable feed rate delivers sufficient cable to the seafloor to follow the bottom so that suspended segments are not created. Bottom types that are rocky or have sharp features can also cause cable failure and are consequently avoided. Accurate deployment of cables is clearly important to ensure that the cable lands in the planned cable routes.

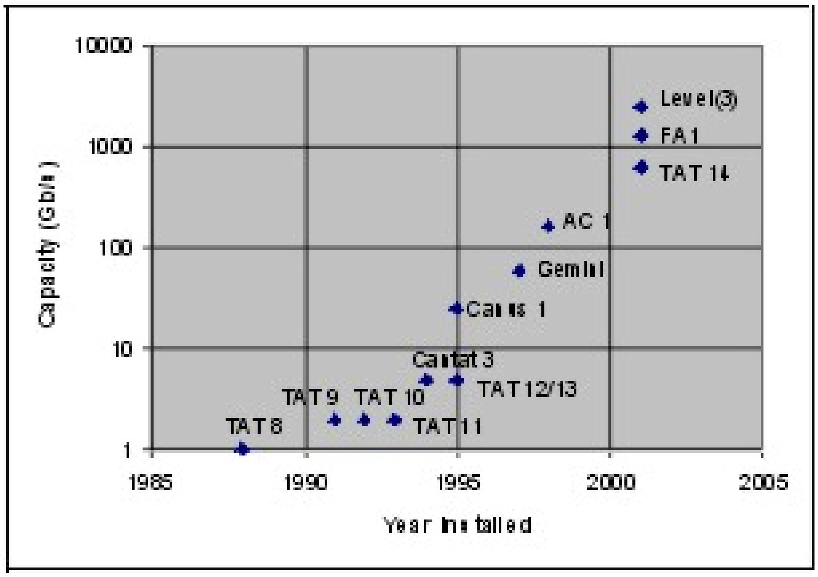


Figure 18: Evolution of subsea telecommunication cable capacity as a function of year.

Human activities are historically the principle failure cause for submarine cables, although the development of effective protection strategies has reduced cable vulnerability dramatically. Burial of cables in shallow water is a standard practice to protect cables from breakage caused by human activities. In relatively shallow water depths, less than 150 m depths, damage caused by anchors from large vessels can extend up to two meters into the seafloor. In greater depths, where anchor damage is unlikely to be a problem, bottom trawling and shell fishing is a hazard to unburied cables. While fishing activity is moving to greater depths, burial in depths beyond 2000 m is considered unnecessary. Bottom characteristics are determined as part of the route planning process to ensure burial is economical.

While hard numbers on cable reliability are difficult to obtain, a combination of historical and anecdotal information from telecommunications cable operators is highly illuminating. Their cables averaged a failure rate of 3.7 faults/1000 km/year from 1957 to 1979, but dropped to 0.44 faults/1000 km/year after 1985, with the reduction attributed to burial of shallow water segments. Deep-water failures on long-haul cables are infrequent, with statistics of recently deployed cable indicating almost a factor of ten fewer faults in deep (>1000 m) as compared to shallow (<1000 m) portions of the cable. Failure of cable equipment is very infrequent, and cable repairs for this reason might occur only once in the 25 year projected life of a telecommunications cable. Less experience is available on observatory cables that will use higher voltages, higher currents, and different repeaters. While there exists a strong foundation of submarine cable technology on which to build new cabled observatories, capabilities unique to such observatories must be developed as well. These include:

- *Undersea break-outs* – The telecommunications industry treats undersea cables as systems routing data from shore landing to shore landing, whereas the scientific community needs to focus on collecting undersea data and delivering it shore. Consequently, highly reliable methods for bringing signals and power to and from the primary cable must be developed.
- *Branching* - Branching is required to construct arbitrary topologies (spur, ring, mesh, etc.) primarily for optimizing sampling array design. Furthermore, redundancy in routing signals and power provides the potential for increasing the reliability of the system, especially since weather conditions might discourage immediate response to a cable break. Thus the ability to branch the primary cable is important for regional cabled observatories.
- *Shore Landings* - Shore landings include the part of the cable running from outside the surf zone to within the support building on shore, requiring the crossing of features such as an active surf zone, variable beach topography, barrier islands, intercoastal waterways, salt marshes, and estuaries. Crossing these environmentally sensitive areas increase costs and raises permitting issues. Consequently, scientific users of cables will likely want to use each shore landing to support multiple cables and loops.
- *Extendibility* – The ability to add additional cable runs, from hundreds of meters to hundreds of kilometers in length, will be necessary to ensure cabled observatories can be adapted to address changing scientific questions. While very long cable runs will require use of industry cable vessels, cable runs of a few hundred kilometers ought to be possible from UNOLS vessels. Techniques for deploying long cable runs from ROVs are already being developed and demonstrated.
- *Plug & play instrumentation* – The ability to easily add and remove instrumentation from the undersea network will be key to the system's success. Sensors must dynamically detect and participate in network services – so-called service discovery. Metadata needed to make use of sensor output must be captured, associated with the correct instrument, and recorded as part of the data archive.
- *Accurate time* – Certain classes of experiments will require highly accurate time registration and measurement, especially acoustic and seismic work.
- *Failure detection/isolation/recovery* – Failures cannot be allowed to propagate from an individual component to the entire system, and must be mitigated with minimum intervention if possible
- *Command/control* – The overall infrastructure will require management. The development of this new technology raises an important question: To what level of reliability should scientific cabled systems be built? The economics driving

reliability for the regional cabled observatory components is not yet well understood. The economic drivers that create the very high demand for reliability in telecommunication cables do not apply to cabled observatories. Defining the multi-way tradeoffs between the benefits of increased capability against the risks of increasing system complexity, costs of development, and costs of maintenance will provide critical guidance in the engineering process.

Expanding the Capabilities of Cabled Observatories

A variety of scientific platforms (tripods, moorings, gliders, AUVs, etc.) are well developed and can be integrated into virtually all of the cabled networks described in the previous six science sections. The regional cabled observatories will both enable and benefit from significant advances in other areas of oceanographic and robotics technology, for example, bottom crawling vehicles, and acoustic communications. There are clear advantages of having both propellor-driven and glider-type autonomous vehicles operate within a cabled observatory, and to have both acoustic and hard-wire communication options available for both vehicles. For example, propeller-driven AUVs typically can carry relatively higher power payloads than glider-type vehicles. However, gliders are capable of mission durations measured in months, whereas propeller-driven AUV mission durations are typically measured in hours. Glider-type vehicles are slower, trading off course control for longer duration. Propeller-driven AUVs have more operational utility within a cabled observatory. Gliders have several advantages for scientific sampling and do not require docking facilities for repowering and data transmission. *Illuminating the Hidden Planet* (2001) identified AUVs as tools for extending the power of cabled observatories. Development of different types of AUVs, docking systems for short-endurance propeller-driven AUVs, and acoustic communications as elements of mobile observatories is underway. While substantial progress has been realized, field programs have been hampered by the expense of deploying communications, power and navigation infrastructures. Cabled observatories can compliment the communications, power and navigation infrastructures required to support some autonomous mobile platforms in the ocean.

By providing a mobile component to a cabled observatory, AUVs enable the characterization of spatial variability on scales less than science node separations. Datasets collected by AUVs can provide key information allowing measurements made at science nodes to be placed in a broader oceanographic context. The mobility of AUVs can also provide a rapid event response and adaptive sampling capability, allowing cabled observatories to extend their presence to regions that the cabled systems are unable to sense. Episodic events such as volcanic eruptions, seafloor slides, weather driven processes, and biological blooms could be characterized by sensors on mobile platforms directed from the cabled observatory.

A large number of AUVs have been developed, and a number are operated routinely in the ocean. Vehicles range from 20 cm to 120 cm in diameter, and from fifty to thousands of kilograms in mass. Development of AUVs is also being shaped by military and commercial markets, which have energized marine technology companies to invest in sensors and subsystems. The result is a rapidly evolving technological base and the establishment of a number of commercial AUV suppliers.

Plans for making propeller-driven AUVs integral elements of cabled observatories include developing robust docking capabilities for short-duration vehicles. This will allow these AUVs to connect to the cabled infrastructure for high-bandwidth communications and battery recharging. Propeller-driven AUVs used by the scientific community typically cruise at about 5 km/hr for about a half a day and are deployed and recovered by ships, small boats or swimmers. A cabled infrastructure with docking stations would allow short-duration propeller-driven vehicles to be operated for extended periods. While a variety of AUV docks have been demonstrated, substantial technical challenges must be overcome to develop fully capable and robust docking systems and propeller-driven AUVs capable of being operated unattended for many months.

A docking capability, once developed, could enable the use of AUVs for servicing of instrumentation not physically connected to the cable infrastructure. The ability to retrieve data acoustically from stand-alone seafloor instruments via an AUV would extend observatory support beyond the cabled infrastructure. Communication with platforms located a distance from a science node could be supported without incurring the cost of a short cable run. Logistical savings would be realized since stand-alone instruments would not require an ROV for deployment and recovery.

Regional cabled observatories will also enable a wide range of acoustic techniques that will represent both research activities in their own right, and greatly augment observatory capabilities. The U.S. Navy Sound Surveillance System (SOSUS) offers an excellent example of a cabled ocean observatory supporting passive acoustic arrays. Developed for military applications during the cold war, SOSUS has been made available in the last decade on a limited basis to the scientific community. Scientific applications such as detection of underwater eruptions, detection and tracking of marine mammals, and determining large scale ocean temperature change as part of acoustic thermometry have provided powerful insight into the use of passive acoustics for oceanographic science. Regional cabled observatories would allow the establishment of a scientific version of SOSUS, with frequency sensitivities and array configurations optimized for scientific applications rather than tracking of ships and submarines.

The ability to have a large number of multi-element acoustic arrays with active elements distributed on the seafloor is particularly attractive and would benefit applications such as acoustic tomography or even moving source tomography (in which an AUV might provide the moving source). Systems cabled into an observatory could be comparatively simple as power would be provided; they would have access to accurate time, and computational elements could be on shore. The latter point is particularly attractive. By placing just the transmit and receive elements in the ocean, and using the high bandwidth of the observatory to move the information to shore to be processed, the more complex hardware and software can be kept on land. Not only does this allow ease of maintenance, it also enables in-service upgrades. As improved algorithms are developed, and greater processing power made available, onshore processing can be improved at will.

Bandwidths of cabled systems would support shore-side processing for all but the most demanding acoustic systems. A typical example would be navigation systems in the low frequency band (7-15 kHz). These systems are routinely used to ranges of about 10 km. Achieving greater ranges would require lower frequencies due to seawater's property of increasing attenuation with increasing acoustic frequency.

Cabled observatories offer unparalleled opportunities for installing permanent acoustic networks to provide communication and navigation services. Particularly exciting is the prospect of employing acoustic communications to extend the communication infrastructure to instruments not physically connected to the cabled network. Instrumentation capable of being self-powered, and requiring relatively small bandwidth for communications would be candidates for being acoustically linked. Such devices would be equipped with an acoustic modem capable of communicating with the cabled acoustic communications network. The computational resources and software complexity of such an acoustic network would be largely on shore, conforming to the paradigm outlined earlier. This is possible because high-bandwidth communications require relatively little computational effort for transmitting information, and because the greatest demand for bandwidth would be for sending data from the instrument to the cabled network. Thus instrumentation would likely carry modems supporting high bandwidth communications to the network, and low bandwidth communications from the network.

The cabled acoustic network would provide a pathway to introduce instrumentation to sites beyond the reach of the cabled infrastructure without installing new cable. Furthermore, such instrumentation would not require an ROV for installation. An acoustic communications network could also be used to communicate with and control both free-swimming AUVs and bottom crawling vehicles. In addition to communications, such an acoustic infrastructure could also be used to supply navigation and tracking services. Not only would this provide much greater flexibility for autonomous vehicle operations, the same systems might provide navigation support for ROV operations, geodesy for instrument placement, and communication support for remote instrumentation not connected to the cable.

Operations and Maintenance

Operations of a cabled observatory will require a high level of interaction between the scientific community and the observatory operator, as there may be substantial competition for observatory resources. Control of community hardware such as sensors and AUVs, intervention ROVs, and spare parts is a familiar problem. Power, bandwidth, and archive space might seem at first to be unlimited, however demands on the facility infrastructure could exceed capabilities, especially should an event like a seafloor eruption create a simultaneous call on resources by observatory users. The time-series nature of an observatory also creates a requirement that the environment surrounding at least some nodes be treated as a limited resource. For example, undisturbed sediment might be critical to certain studies. Even the laying of extension cables may require review to ensure that new cables do not interfere with existing cable runs or disturb study regions on the seafloor. Interference between experiments might be a significant concern. Light, chemical, or radiated acoustic noise might be necessary for some users, and a noise factor for others. The acoustic spectrum might also encounter conflicting demands.

In contrast to a telecommunication cable, seafloor observatories are likely to be routinely attended by ships, ROVs, or divers as various science instruments are deployed, maintained, and recovered. Cabled observatories might be analogous to deep-water oil production facilities, where large networks of complex hardware are installed on the seafloor. Although designed to be reliable, problems requiring intervention are expected. Seafloor oil production equipment design is therefore heavily driven by ease of maintenance concerns. Designing for maintenance will be critical for the success of cabled observatories as well. Thus design teams for cabled observatories should draw heavily on the knowledge of operational personnel experienced not only in the design of submarine cable power and telemetry systems, but also in the operation and maintenance of these systems and other complex subsea equipment.

A range of platforms will support maintenance and repair. UNOLS vessels will support intervention with ROVs, use lift systems to recover major components to the surface for repair or replacement, or support direct deployment and recovery of some elements from the surface. Use of systems like benthic elevators, developed to support scientific ROV operations, will provide additional deployment and recovery options. Simple devices to automate processes like cleaning windows on cameras will be required. More specialized technologies may be created to take advantage of the high bandwidth, high power available onsite. Local remotely operated actuators analogous to the Space Station Remote Manipulator System, or ROVs wired into the subsea cable, could provide an intervention capability independent of ships and insensitive to weather windows. Such capabilities would be extremely useful for science activities as well. Hybrid AUV-ROVs do not exist yet, but have been identified by the oil and gas industry as an attractive technology for maintaining distributed subsea facilities. These hybrids would be capable of operating as a locally deployed ROV when connected to the subsea cable infrastructure, and of disconnecting and reconnecting to move to new service sites.

Science Box 7: Operational considerations for optimization of scientific productivity using a cabled observatory

Facility operation will be a significant commitment, and substantial efforts will be required to ensure operations costs are controlled. These begin with good engineering practice – for example, system testing and prototyping, designing to mitigate corrosion, building in fault tolerance, using redundancy where possible and practical, and building systems that can be repaired *in situ* where possible (especially for deep water elements of the system). Procedures must be documented and refined. Tool kits for repairs and intervention must be created and maintained. Operational procedures for optimizing productivity of support vessels must be created as well, for example coordinating visits to sites.

How might a researcher use the regional scale cabled observatory? Considering relatively simple questions of access creates many questions, including:

Table 3: Typical Questions for a Cabled Observatory Researcher

1) Writing the proposal for the science effort that requires installing instrumentation on the observatory requires knowledge of the following issues:
   a. How are installation and recovery costs covered? Who determines how much ROV or diver time is required for a specific operation?
   b. Who pays for engineering support from observatory staff (if any)?
   c. Are their running costs for operating an instrument as part of the observatory?
   d. If data are centrally managed, are there data management and distribution costs?
2) How does an investigator work with the observatory staff to ensure sensor functionality prior to deployment
   a. Who are points of contact?
   b. Are there points of contact related to coordination issues with other experiments? For example, what if an investigator requires the full power capacity of a science node for intervals?
   c. Are there standards to which the instrument must conform?
   d. Are there specific tests the instrument must pass? If so, who carries them out? Are there certain instruments that are 'prequalified?'
   e. Is there a shore-based (or easily accessible) test node to ensure that sensors and connections are properly configured before deployment?
   f. Is an environmental impact a consideration?
      i. Is physical congestion at scientifically interesting sites a consideration? If so, what are the mechanisms for resolving conflicts? When does this become a factor in the proposal process?
      ii. Will disturbance of environment compromise subsequent experiments?
   g. What are the demands on observatory resources, including:
      i. Power
      ii. Bandwidth

iii. Acoustic spectrum
iv. AUVs
v. ROVs
vi. Onsite intervention capabilities

h. What are the priorities for timely experiment operation (e.g. low except during eruption event, then very high)?

3) Deployment

a. Who is responsible for deployment tasks? Who is on the ship?
b. Who is responsible for making sure instruments work? What is the role of the user in this process? How is the deployment scheduled?
c. How are experiment operations initiated? Who decides when a system is operational?

4) Operation

a. If the instrument is used in a reactive mode, what procedures are in place to either automate or ensure timely human interaction?
b. How are conflicts resolved when resource demands of an experiment conflict with another experiment? When are these resolved, and by what mechanism? What is the responsibility of the facility operator in this process?
c. How are data quality controlled? Who is responsible for creating the QC tools?
d. How are repairs to failed instruments prioritized?
e. How are data made available? Who makes tools for working with the data available?

One of the general issues concerning the operation of observatory infrastructure involves the definition of the respective responsibilities of the operator and the users. Where does the observatory infrastructure end and the experiments begin? What kind of governance model would be best suited for a scientifically-driven cabled observatory? Lowering the threshold of participation for the oceanographic community to put instruments in the oceans, and to work productively with the resulting data, will be key to the success of the cabled observatory facilities. Clearly, active and meaningful participation of scientists in all aspects and phases will be vital to ensure that science rather than engineering drives the cabled observatory culture.

[ER19]

Closing Remarks

This section addresses three subtopics: (a) examples of applications and uses of cabled observatories that were beyond the scope of this report, (b) issues and challenges for the successful implementation and utilization of cabled observatories, and (c) relationships of cabled observatories with other observational programs.

Other Applications of Cabled Observatories

The scope of the SCOTS activity was necessarily limited by the short length of time available for completion of the report and the range of expertise of the Committee and Workshop participants. However, additional important applications for cabled observatories were identified by individuals who responded to SCOTS questionnaires and by SCOTS Workshop participants. For example, cabled systems would be ideally suited for high latitude studies under ice sheets where direct surface access is not always, or in some cases never, possible. Cables would run from shore under the ice, and the sensors and systems would likely need to be installed by ships during ice-free periods or by submarines, ROVs with long tethers, or AUVs in permanent ice covered areas. More generally, high latitude oceanographic research could benefit from use of the cabled approach because of both ice and adverse weather conditions. Presently, oceanographic research in these regions is generally limited to specific seasons leaving us devoid of annual cycle data.

Equipping observatories with seismometers is a well-accepted methodology for remote imaging of the Earth's interior. Many existing cabled observatory technologies for sensing the ocean environment limit scientists to the sometimes routine task of monitoring what drifts by until something exciting happens. Methods similar to those used by the geophysicists to remotely image the ocean's interior require development to maximize the interdisciplinary utility of cabled observatories. Routine remote imaging of the ocean on regional scales is presently limited to horizontal arrays of vertically-profiling acoustic Doppler current sensors or inverted echo sounders. Water column Light Detection and Ranging (LIDAR) systems have been used to determine *in situ* optical properties from ships and planes. Installation of LIDAR systems on cabled observatories could take advantage of the high power and data rates available. Maximizing their utility requires investment in the development of advanced technologies for specific applications, such as single, several color, Raman and polarized transmit and receive systems, and in forward and inverse models that correlate these data with parameters measured *in situ*. In coastal applications, the combined acoustic/LIDAR/optics imaging systems are a potential interface between *in situ* bottom measurements and remotely sensed spatial data from satellites and high-frequency radars. Acoustic tomography can further expand the three-dimensional imaging capability for the ocean's interior over large control volumes, complementing the capabilities of subsurface platforms that are more spatially limited and virtually incapable of synoptic sampling. Acoustic tomography is especially well suited for cabled systems, again because of high power and real-time data transmission needs. One could view an acoustic tomographic array as providing large scale, lower resolution 3-dimensional synoptic data while AUVs, gliders and fixed position assets enable finer resolution spatial data in selected areas. In addition, ocean acoustic thermography could similarly utilize cabled assets distributed over the globe.

Other scientific uses of cabled observatories are emerging and will continue to emerge in the future. There are many potential operational uses for cabled observatories as well. Cabled systems are well-suited to support instrumentation for acoustically tracking fish, a method already demonstrated to be feasible. Other examples include: prediction and monitoring of harmful algal blooms, invasive species episodes, eutrophication events, sediment transport and beach erosion, fate and effects of oil spills and other related environmental contaminants, status of fisheries, coral reefs, and kelp beds. In addition, operational cables of opportunity could make use of the sampling technologies developed for the scientific cabled observatories. Cables of opportunity not only include the retired telecommunications cables, but also could potentially include existing cables operated by the Navy (SOSUS) or the oil industry. For example, the fiber-optic communications backbone between oil platforms in the Gulf of Mexico also could be used to transmit scientific data streams from systems developed for the scientific observatories. Finally, it should be noted that cabled observatories are ideal for educational and public outreach activities. For example, video and other oceanographic information could be easily transmitted to aquaria and museums worldwide.

Technical Challenges and Other Issues

The report has generally centered upon new scientific opportunities afforded by cabled observatories. Some of the technological challenges facing cabled observatories were described in previous sections. Here we summarize a few of the important problems that were mentioned in questionnaires and during Workshop discussions.

There is a clear advantage in burying cables in the coastal zone to minimize exposure to perturbation, damage, or loss of cables (e.g., trawling, fishing). Further, scientists and engineers acknowledged concerns over sharing cable power and bandwidth between deep ocean and coastal measurements because of this increased hazard risk. However, the coastal zone is a region that can benefit greatly from cabled systems. A solution to this dilemma needs to be found. Dual use may not be an acceptable practice and increased cost would thus be incurred. Cables will likely be placed in geophysically vulnerable locations such as near faults, hydrothermal vents, submarine canyons, and slumps, so breaks in cable lines and damage to scientific nodes are of concern. Different cable configurations and redundancies need to be factored into system design. Likewise, sensors and systems need to be interfaced so as to minimize potential system failure. Cabled observatories are exceptionally well-suited for studies of the ocean bottom environment. However, this environment will be necessarily disturbed, causing perturbations of the desired observations and measurements. Multiple users of the cable may have cross purposes (e.g., one investigator may want to do a controlled experiment through manipulation and perturbation, while another requires pristine natural conditions). There may be other obstacles for cable use as well. These could include restrictions on sites or cable runs because of environmental impact and defense restrictions. Planning for the replacement of cable hardware and software that will become obsolete at some point during the lifetime of the observatory needs to be considered in the design phase. For example, the ability to phase in system or infrastructure upgrades is necessary to maintain continuity of operations and, more importantly, scientific data sets. Management and control of cabled observatories and their resulting data sets are critical issues that will need considerable discussion in the implementation phase.

Economic aspects of and budget allocations for cabled versus other ocean observational approaches were frequent points of concern and discussion. There are clearly excellent arguments for and against use of different sampling methodologies for specific scientific research. It is well beyond the scope of this report to treat this point, which clearly deserves in-depth study and will be addressed by the National Research Council (NRC) Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research.

Relationships with Other Observational Programs

The SCOTS Committee and Workshop participants identified several synergies with other observational programs including those that will focus on operational applications as well as purely research studies. There is strong community consensus that all available ocean sampling assets need to be optimally utilized because of the complexities of the ocean environment and its diverse processes. Multi-platform sampling approaches and well-integrated modeling components are manifestations of this viewpoint. It is also likely that programs with primarily operational objectives will be used for research and those focusing on science issues will be simultaneously used for operational oceanography. An over-riding theme was that multi-disciplinary and interdisciplinary approaches will be integral to all cabled observatories. Sharing of data collected and distributed in real-time or near real-time was a generally anticipated mode of community culture. The sharing of data collected from developing instrumentation remains a discussion point.

The open-data policy expected for cabled observatories will accelerate collaborations among oceanographers and facilitate major scientific advances for scientists participating in a variety of oceanographic programs within the United States and internationally. Organized programs such as those funded under the auspices of the National Science Foundation, Office of Naval Research, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, Minerals Managements Service, Geological Survey, the Environmental Protection Agency or interagency organizations, such as the National Ocean Partnership Program, can all potentially benefit from cabled observatories. Ongoing NSF programs (e.g., Coastal Ocean Processes, RIDGE, and other emerging interdisciplinary projects), as well as the developing U.S. and Global Ocean Observing Systems, will likely benefit from future cabled observatories and vice versa.

Finally, it should be noted that the present report represents an effort to facilitate the advancement of ocean sciences through considerations of new technologies, particularly cabled observatories. Previous reports including the *Millennium Report* and *Illuminating the Hidden Planet Report* have motivated and facilitated this report. The present report represents an intermediate, evolutionary step toward the realization of observatory systems that will likely lead to major scientific breakthroughs and paradigm shifts in the rapidly advancing field of oceanography. The forthcoming NRC report on Implementation of a Seafloor Observatory Network for Oceanographic Research will hopefully benefit from the present report and is expected to set the context for future cabled and other observatory methods and programs. In closing, it is important to thank the many hardworking individuals who were willing to share their thoughts and ideas with the entire community and make this report possible.

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Toward a U.S. Plan for an Integrated, Sustained Ocean Observing System
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APPENDICES

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OTHER

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Appendix 3: Frequently Asked Questions (FAQ)

<u>Ocean Observatories Initiative</u>

What is the MRE?

The MRE (Major Research Equipment; now the MREFC-Major Research Equipment and Facilities Construction) account is a National Science Foundation (NSF)-wide capital asset account that provides funding for the establishment of major science and engineering infrastructure having costs ranging from several tens to hundreds of millions of dollars. In the MREFC context, "infrastructure" is used interchangeably with "tools." NSF established this account in FY 1995 to promote effective planning and management for the support of sizable investments made over a limited period of time.

The MREFC account supports state-of-the-art tools that are centralized in nature, integrated systems of leading-edge instruments, and distributed nodes of information that serve as shared-use networked infrastructure in advancing one or more fields of scientific study. Examples include accelerators, telescopes, research vessels, aircraft, earthquake simulators, networked high-tech research platforms, advanced computing resources, digital libraries, and large databases. The Division of Ocean Sciences (OCE) hopes that the Ocean Observatories Initiative (OOI) will be added to this list in the near future.

The MREFC process begins with internal requests from NSF Divisions for large equipment items or facilities that are proposed to the NSF Director and the National Science Board (NSB) with the hope that they are approved and eventually put into a NSF budget request. Currently, the OOI has been approved by the NSB and hopefully will be included in NSF's FY04 budget request that will go to the Office of Management and Budget in February 2003. In expectation that the OOI is in the FY04 budget request, OCE is continuing the implementation planning for the OOI.

What is the Ocean Observatory Initiative (OOI)?

With funding from the MREFC account, OCE plans to construct an integrated observatory network that will provide the oceanographic research and education communities with a new mode of access to the ocean. The OOI has three elements: 1) a network of regional cabled observatories on the seafloor spanning multiple geological and oceanographic features and processes, 2) several relocatable deep-sea buoys that could be deployed in harsh environments such as the Southern Ocean, and 3) new construction or enhancements to existing facilities leading to an expanded network of coastal observatories.

How will the science be funded? How will the network continue to be funded?

As with all MREFC projects, the science that will result from the establishment of this infrastructure must be supported by the Division from which the request originated, in this case OCE. Normally, this additional support comes from budget increases that follow the capitalization of infrastructure from the MREFC investment. In the same manner, continued support for the network must come from funds appropriated to OCE.

Will the observatory data be open to the community?

Yes, the data collected by the OOI will be subject to open access, real or near-real time availability. Some delays in accessibility may be needed to ensure the quality of some datasets. In instances where PIs place third-party sensors on observatory infrastructure, there may be a moratorium of one year or less to ensure that the sensors are operating properly.

How might the OOI be managed? What is the mechanism to participate in observatory science?

Two phases of management are envisioned. The first will oversee the acquisition, installation and implementation of observing infrastructure. Once established, the second management phase will oversee the operation and continuing development of the system.

The management structure for the acquisition and implementation phase is based on a structure that has been successfully used by the Ocean Drilling Program for many years. The day-to-day management, coordination, and oversight of the Regional and Moored Buoy components of the OOI will be the responsibility of an Executive Director of the OOI Program Office established through a Co-operative Agreement with NSF. This Director will be accountable to an Executive Committee under which will be established Scientific and Technical Advisory Committees. The Executive and Advisory Committees will draw their membership from individuals with expertise in ocean observing science and engineering. The Advisory Committees will have the power to establish subcommittees when more specific advice is needed. Subcontracts for the Cable and Moored Buoy components will be established to provide the specified ocean observation capabilities. The awardees of these subcontracts will work closely with the community-based Technical and Scientific Advisory Committees, the Director, and NSF Program staff. International partners that may eventually wish to contribute to the OOI would establish agreements with NSF. The existing National Oceanographic Partnership Program (NOPP) structure will facilitate participation from other Federal Agencies.

Management of the coastal observatory component of the OOI may differ from the regional and cabled systems discussed above as, in addition to new systems, projects may involve enhancements to existing systems that would already have management structures in place.

Close coordination will be maintained among all grantees, NSF, and the NOPP Ocean Information Technology Infrastructure Steering Committee to ensure that there will be common data handling protocols and standards in addition to effective communication amongst the systems. NSF will also work to ensure effective international coordination, and to keep all activities consistent with and synergistic to the goals of the National Integrated Ocean Observing System (IOOS) effort.

Following the envisioned five-year implementation phase, a separate competition will be held for operations and maintenance of the regional and buoyed observatories. It is envisioned that the management structure for this phase could resemble the highly effective structure of the UNOLS fleet.

Scientific use of infrastructure related to the OOI will be on a peer-reviewed basis where the highest quality proposals will be awarded the funds needed to place appropriate instrumentation on the ocean observatory network infrastructure.

SCOTS

What does SCOTS stand for?

Scientific Cabled Observatories for Time Series (SCOTS) is a committee that was established by the NSF's OCE to provide advice on the scientific rationale and implementation of a network of regional cabled observatories as outlined in the OOI.

Why is this activity focusing on cabled observatories?

To continue planning for the OOI and to obtain community input on its three components, there are currently three activities underway that will provide NSF with advice on the coastal, moored buoy, and regional observatory components of the OOI. In addition to these activities, OCE has sponsored a National Research Council (NRC) study to place the results of these three activities in the context of current research priorities as well as provide recommendations for an overall implementation plan for the OOI. This NRC study will also provide a clear statement on the role of the NSF observing system within the larger National IOOS being planned by Ocean.US.

The first activity, developed by the Time Series Team of the Ocean Observing Panel for Climate (OOPC) of the Global Ocean Observatory System (GOOS), will develop a plan for the deployment of a global network of moored buoy systems for multi-disciplinary science. The second activity was a NSF sponsored workshop on Coastal Observing Systems for Research run by the Coastal Ocean Process Program. The report from this workshop will be released soon. The third activity is the SCOTS Committee that will provide advice on the scientific rationale and implementation of a network of regional cabled observatories. The reports from the three activities will serve as input to the NRC study described above.

All of these activities are overseen by the Dynamics of Earth and Ocean Systems (DEOS) committee, which is a planning effort by the academic research community and the NSF to lay the groundwork for a network of ocean observatories. The overall objective of DEOS is to provide a focus for coordinated scientific planning that identifies the science and engineering trends, opportunities, and considerations for making sustained research observations from fixed ocean observatories. The DEOS website, which includes a list of FAQs to complement this one, can be found at http://www.coreocean.org/deos/.

What does NSF need from the SCOTS workshop?

To further the planning for the cabled portion of the OOI, NSF seeks community input to define the scientific problems that require or would most effectively be addressed by regional-scale cabled observatory networks. In addition, input is needed for the design and location of these cabled systems. Taking into account previous planning documents, NSF has requested that the SCOTS committee write a report to address the above task and identify possible strategies needed to carry out the science identified via cabled observatories. The strategies considered will include criteria for locating cabled observatories and other design considerations (such as sensor requirements, data transfer, power needs, etc.). An overriding theme will involve optimal utilization of cabled observatories for a multiplicity of research activities. The SCOTS committee will base its findings on recent reports that outline ocean science research priorities, existing cabled observatory strategies and implementation plans, community input, and the committee's expertise.

How were people invited to the SCOTS workshop?

Funds to support the travel of 30 participants were provided to the SCOTS committee although the workshop was open to anyone who wished to attend. A list of attendees of this workshop will be posted on the SCOTS website: http://www.COREocean.org/DEOS.

General Ocean Observing

What is Ocean.US?

Ocean.US was created by NOPP in late 2000 to coordinate activities related to the establishment of an Integrated and sustained Ocean Observing System (IOOS). Information from this system will serve national needs for: detecting and forecasting oceanic components of climate variability, facilitating safe and efficient marine operations, ensuring national security, managing resources for sustainable use, preserving and restoring healthy marine ecosystems, mitigating natural hazards, ensuring public health. More information on Ocean.US can be found at: http://www.ocean.us.net/.

How much money are they anticipating?

It is anticipated that the annual cost of a fully-realized, integrated and sustained coastal and open ocean observing system in constant dollars is $500M; the new investment required to initiate a sustainable path to full implementation of the IOOS is $138M. These costs do not specifically address requirements for the satellite-based remote sensing. More details on the IOOS plan can be found on the Ocean.US web page.

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