EARTH AND ENVIRONMENT

A 2020 Vision for Ocean Science

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THE GLOBAL OCEAN is the last physical frontier on Earth. Covering 70 percent of the planetary surface, it is the largest, most complex biome we know. The ocean is a huge, mobile reservoir of heat and chemical mass. As such, it is the "engine" that drives weather-climate systems across the ocean basins and the continents, directly affecting food production, drought, and flooding on land. Water is effectively opaque to electromagnetic radiation, so the seafloor has not been as well mapped as the surfaces of Mars and Venus, and although the spatial relationships within the ocean basins are well understood to a first order, the long- and short-term temporal variations and the complexities of ocean dynamics are poorly understood.

The ultimate repository of human waste, the ocean has absorbed nearly half of the fossil carbon released since 1800. The ocean basins are a source of hazards: earthquakes, tsunamis, and giant storms. These events are episodic, powerful, often highly mobile, and frequently unpredictable. Because the ocean basins are a vast, but finite, repository of living and non-living resources, we turn to them for food, energy, and the many minerals necessary to sustain a broad range of human lifestyles. Many scientists believe that underwater volcanoes were the crucible in which early life began on Earth and perhaps on other planets. The oceans connect all continents; they are owned by no one, yet they belong to all of us by virtue of their mobile nature. The oceans may be viewed as the common heritage of humankind, the responsibility and life support of us all.

OCEAN COMPLEXITY

Our challenge is to optimize the benefits and mitigate the risks of living on a planet dominated by two major energy sources: sunlight driving the atmosphere and much of the upper ocean, and internal heat driving plate tectonics and portions of the lower ocean. For more than 4 billion years, the global ocean has responded to and integrated the impacts of these two powerful driving forces as the Earth, the oceans, the atmosphere, and life have co-evolved. As a consequence, our oceans have had a long, complicated history, producing today's immensely complex system in which thousands of physical, chemical, and biological processes continually interact over many scales of time and space as the oceans maintain our planetary-scale ecological "comfort zone."

Figure 1 captures a small fraction of this complexity, which is constantly driven by energy from above and below. Deeper understanding of this "global life-support system" requires entirely novel research approaches that will allow broad spectrum, interactive ocean processes to be studied simultaneously and interactively by many scientists—approaches that enable continuous *in situ* examination of linkages among many processes in a coherent time and space framework. Implementing these powerful new approaches is both the challenge and the vision of next-generation ocean science.

HISTORICAL PERSPECTIVE

For thousands of years, humans have gone to sea in ships to escape, to conquer, to trade, and to explore. Between October 1957 and January 1960, we launched the first Earth-orbiting satellite and dove to the deepest part of the ocean. Ships, satellites, and submarines have been the mainstays of spatially focused oceanographic research and exploration for the past 50 years. We are now poised on the next threshold of technological breakthrough that will advance oceanic discovery; this time, exploration will be focused on the time domain and interacting processes. This new era will draw deeply on the emergence, and convergence, of many rapidly evolving new technologies. These changes are setting the scene for what Marcel Proust called "[t]he real voyage of discovery, [which] lies not in seeking new landscapes, but in having new eyes."

In many ways, this "vision" of next-generation oceanographic research and

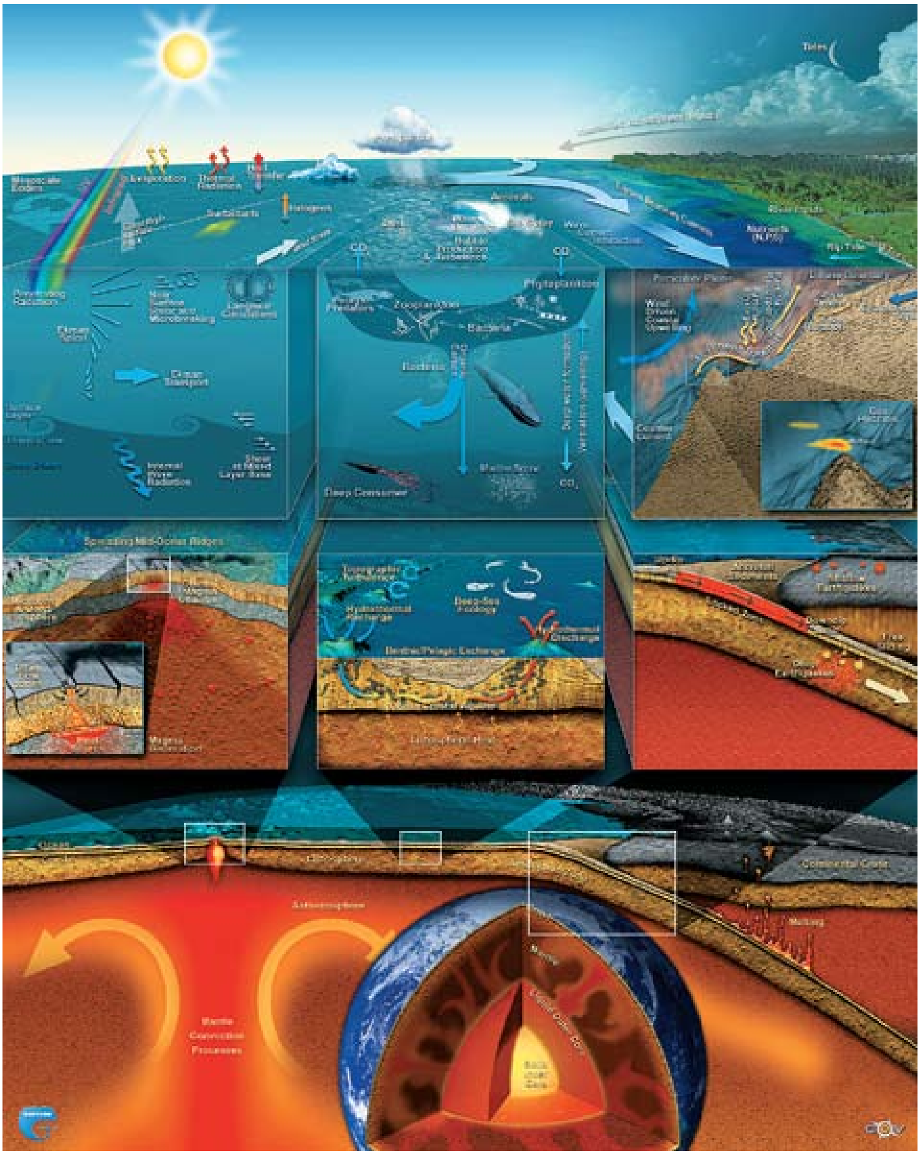

FIGURE 1.

Two primary energy sources powerfully influence the ocean basins: sunlight and its radiant energy, and internal heat with its convective and conductive input. Understanding the complexity of the oceans requires documenting and quantifying—in a well-defined time-space framework over decades—myriad processes that are constantly changing and interacting with one another.

Illustration designed by John Delaney and Mark Stoermer;
created by the Center for Environmental Visualization (CEV) for the NEPTUNE Program.

education involves utilizing a wide range of innovative technologies to simultaneously and continuously "see," or sense, many different processes operating throughout entire volumes of the ocean *from a perspective within the ocean.* Some of these same capabilities will enable remote *in situ* detection of critical changes taking place within selected ocean volumes. Rapid reconfiguration of key sensor arrays linked to the Internet via submarine electro-optical cables will allow us to capture, image, document, and measure energetic and previously inaccessible phenomena such as erupting volcanoes, major migration patterns, large submarine slumps, big earthquakes, giant storms, and a host of other complex phenomena that have been largely inaccessible to scientific study.

THE FOURTH PARADIGM

The ocean has been chronically under-sampled for as long as humans have been trying to characterize its innate complexity. In a very real sense, the current suite of computationally intensive numerical/theoretical models of ocean behavior has outstripped the requisite level of actual data necessary to ground those models in reality. As a consequence, we have been unable to even come close to useful predictive models of the real behavior of the oceans. Only by quantifying powerful episodic events, like giant storms and erupting volcanoes, within the context of longer-term decadal changes can we begin to approach dependable predictive models of ocean behavior. Over time, as the adaptive models are progressively refined by continual comparison with actual data flowing from real systems, we slowly gain the ability to predict the future behavior of these immensely complex natural systems. To achieve that goal, we must take steps to fundamentally change the way we approach oceanography.

This path has several crucial steps. We must be able to document conditions and measure fluxes *within the volume of the ocean, simultaneously and in real time,* over many scales of time and space, regardless of the depth, energy, mobility, or complexity of the processes involved. These measurements must be made using co-located arrays of many sensor types, operated by many investigators over periods of decades to centuries. And the data must be collected, archived, visualized, and compared immediately to model simulations that are explicitly configured to address complexity at scales comparable in time and space to the actual measurements.

This approach offers three major advantages: (1) The models must progressively emulate the measured reality through constant comparison with data to capture the real behavior of the oceans in "model space" to move toward more predictive simulations; (2) When the models and the data disagree, assuming the data are valid, we must immediately adapt at-sea sensor-robot systems to fully characterize the events that are unfolding because they obviously offer new insights into the complexities we seek to capture in the failed models; (3) By making and archiving all observations and measurements in coherently indexed time and space frameworks, we can allow many investigators (even those not involved in the data collection) to examine correlations among any number of selected phenomena during, or long after, the time that the events or processes occur. If the archived data are immediately and widely available via the Internet, the potential for discovery rises substantially because of the growing number of potential investigators who can explore a rapidly expanding spectrum of "parameter space." For scientists operating in this data-intensive environment, there will be a need for development of a new suite of scientific workflow products that can facilitate the archiving, assimilation, visualization, modeling, and interpretation of the information about all scientific systems of interest. Several workshop reports that offer examples of these "workflow products" are available in the open literature [1, 2].

EMERGENCE AND CONVERGENCE

Ocean science is becoming the beneficiary of a host of powerful *emergent* technologies driven by many communities that are entirely external to the world of ocean research—they include, but are not limited to, nanotechnology, biotechnology, information technology, computational modeling, imaging technologies, and robotics. More powerful yet will be the progressive *convergence* of these enabling capabilities as they are adapted to conduct sophisticated remote marine operations in novel ways by combining innovative technologies into appropriate investigative or experimental systems.

For example, computer-enabled support activities must include massive data storage systems, cloud computing, scientific workflow, advanced visualization displays, and handheld supercomputing. Instead of batteries and satellites being used to operate remote installations, electrical power and the vast bandwidth of optical fiber will be used to transform the kinds of scientific and educational activities that can be conducted within the ocean. Adaptation of industry-standard electro-optical cables for use in oceanographic research can fundamentally change the nature of human telepresence throughout the full volume of the oceans by introducing unprecedented but routinely available power and bandwidth into "ocean space." High-resolution optical and acoustic sensing will be part of the broader technology of "ocean imaging systems." These approaches will include routine use of high-definition video, in stereo if needed, as well as high-resolution sonar, acoustic lenses, laser imaging, and volumetric sampling. Advanced sensor technologies will include chemical sensing using remote, and mobile, mass spectrometers and gas chromatographs, eco-genomic analysis, and adaptive sampling techniques.

AN INTEGRATED APPROACH

After decades of planning [3, 4], the U.S. National Science Foundation (NSF) is on the verge of investing more than US$600 million over 6 years in the construction and early operation of an innovative infrastructure known as the Ocean Observatories Initiative (OOI) [4]. The design life of the program is 25 years. In addition to making much-needed high-latitude and coastal measurements supported by relatively low-bandwidth satellite communications systems, this initiative will include a transformative undertaking to implement electro-optically cabled observing systems in the northeast Pacific Ocean [5-7] off the coasts of Washington, Oregon, and British Columbia, as illustrated in Figure 2.[1]

These interactive, distributed sensor networks in the U.S. and Canada will create a large-aperture "natural laboratory" for conducting a wide range of long-term innovative experiments within the ocean volume using real-time control over the entire "laboratory" system. Extending unprecedented power and bandwidth to a wide range of interactive sensors, instruments, and robots distributed throughout the ocean water, at the air-sea interface, on the seafloor, and below the seafloor within drill holes will empower next-generation creativity and exploration of the time domain among a broad spectrum of investigators. The University of Washington leads the cabled component of the NSF initiative, known as the Regional Scale Nodes (formerly known, and funded, as NEPTUNE); the University of Victoria leads the effort in Canada, known as NEPTUNE Canada. The two approaches were conceived jointly in 2000 as a collaborative U.S.-Canadian effort. The Consortium for Ocean Leadership in Washington, D.C., is managing and integrating the entire OOI system for NSF. Woods Hole Oceanographic Institution and the University of California, San Diego, are responsible for overseeing the Coastal-Global and Cyber-Infrastructure portions of the program, respectively. Oregon State University and Scripps Institution of Oceanography are participants in the Coastal-Global portion of the OOI.

[1] www.interactiveoceans.ocean.washington.edu

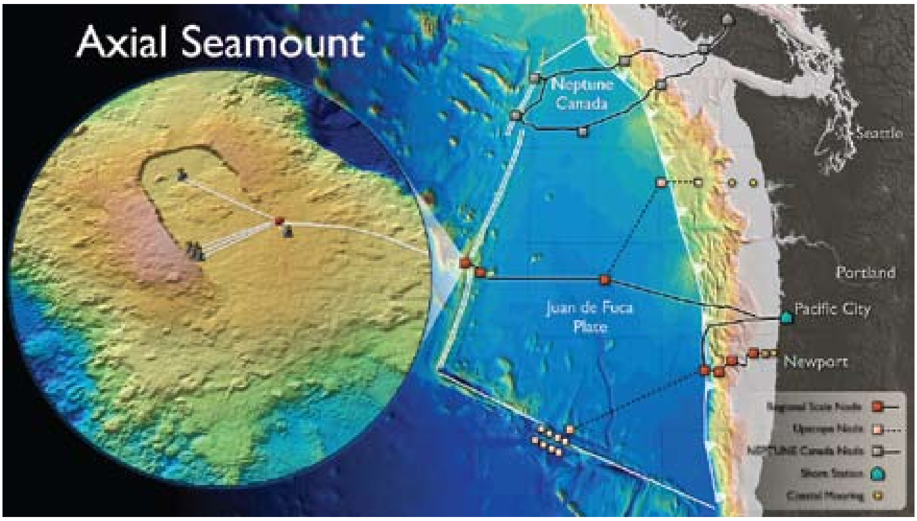

FIGURE 2.
A portion of the OOI focuses on the dynamic behavior of the Juan de Fuca Plate and the energetic processes operating in the overlying ocean and atmosphere. Recent modifications in the Regional Scale Nodes (RSN) have focused on delivery of the elements shown in red, and the pink components are future expansion. The inset shows the crest of Axial Seamount along the active Juan de Fuca Ridge. Each square block site will provide unprecedented electrical power and bandwidth available for research and education. Many of the processes shown in Figure 1 can be examined at the sites here.

Image created by CEV for OOI-RSN.

The cabled ocean observatory approach will revolutionize ocean science by providing interactive access to ocean data and instruments 24/7/365 over two to three decades. More than 1,200 kilometers of electro-optical submarine cable will deliver many tens of kilowatts of power to seafloor nodes, where instruments that might spread over a 50 km radius for each node will be plugged in directly or via secondary extension cables. The primary cable will provide between 2.5 and 10 gigabit/sec bandwidth connectivity between land and a growing number of fixed sensor packages and mobile sensor platforms. We expect that a host of novel approaches to oceanography will evolve based on the availability of *in situ* power and bandwidth. A major benefit will be the real-time data return and command-control of fleets of remotely operated vehicles (ROVs) and autonomous underwater vehicles

FIGURE 3.
Next-generation scientists or citizens. This virtual picture shows a deep ocean octopus, known as Grimpoteuthis, *and a portion of a submarine hydrothermal system on the Juan de Fuca Ridge. Such real-time displays of 3-D HD video will be routine within 5 years.*

Graphic designed by Mark Stoermer and created by CEV for NEPTUNE in 2005.

(AUVs). The infrastructure will be adaptable, expandable, and exportable to interested users. Data policy for the OOI calls for all information to be made available to all interested users via the Internet (with the exception of information bearing on national security).

Hardwired to the Internet, the cabled observatories will provide scientists, students, educators, and the public with virtual access to remarkable parts of our planet that are rarely visited by humans. In effect, the Internet will be extended to the seafloor, with the ability to interact with a host of instruments, including HD video live from the many environments within the oceans, as illustrated in Figure 3. The cabled observatory systems will be able to capture processes at the scale of the tectonic plate, mesoscale oceanic eddies, or even smaller scales. Research into representative activities responsible for climate change, major biological productivity at the base of the food chain, or encroaching ocean acidification (to name a few) will be readily conducted with this new infrastructure. Novel studies of mid-ocean spreading centers, transform faults, and especially processes in the subduction zone at the base of the continental slope, which may trigger massive earthquakes in the Pacific Northwest, will also be addressable using the same investment in the same cabled infrastructure.

This interactive ocean laboratory will be enabled by a common cyberinfrastructure that integrates multiple observatories, thousands of instruments, tens of thousands of users, and petabytes of data. The goals of the cabled ocean observatory can be achieved only if the at-sea portion is complemented by state-of-the-art information technology infrastructure resulting from a strong collaborative effort between computer scientists and ocean scientists. Such collaboration will allow scientists to interact with the ocean through real-time command and control of sensors; provide models with a continuous data feed; automate data quality control and calibration; and support novel approaches to data management, analysis, and visualization.

WHAT IS POSSIBLE?

Figure 4 on the next page depicts some of the potentially transformative capabilities that could emerge in ocean science by 2020. In the long term, a key element of the introduction of unprecedented power and bandwidth for use within the ocean basins will be the potential for bold and integrative designs and developments that enhance our understanding of, and perhaps our ability to predict, the behavior of Earth, ocean, and atmosphere interactions and their bearing on a sustainable planetary habitat.

CONCLUSION

The cabled ocean observatory merges dramatic technological advancements in sensor technologies, robotic systems, high-speed communication, eco-genomics, and nanotechnology with ocean observatory infrastructure in ways that will substantially transform the approaches that scientists, educators, technologists, and policymakers take in interacting with the dynamic global ocean. Over the coming decades, most nations will implement systems of this type in the offshore extensions of their territorial seas. As these systems become more sophisticated and data become routinely available via the Internet, the Internet will emerge as the most powerful oceanographic research tool on the planet. In this fashion, the legacy of Jim Gray will continue to grow as we learn to discover truths and insights within the data we already have "in the can."

While the cabled observatory will have profound ramifications for the manner

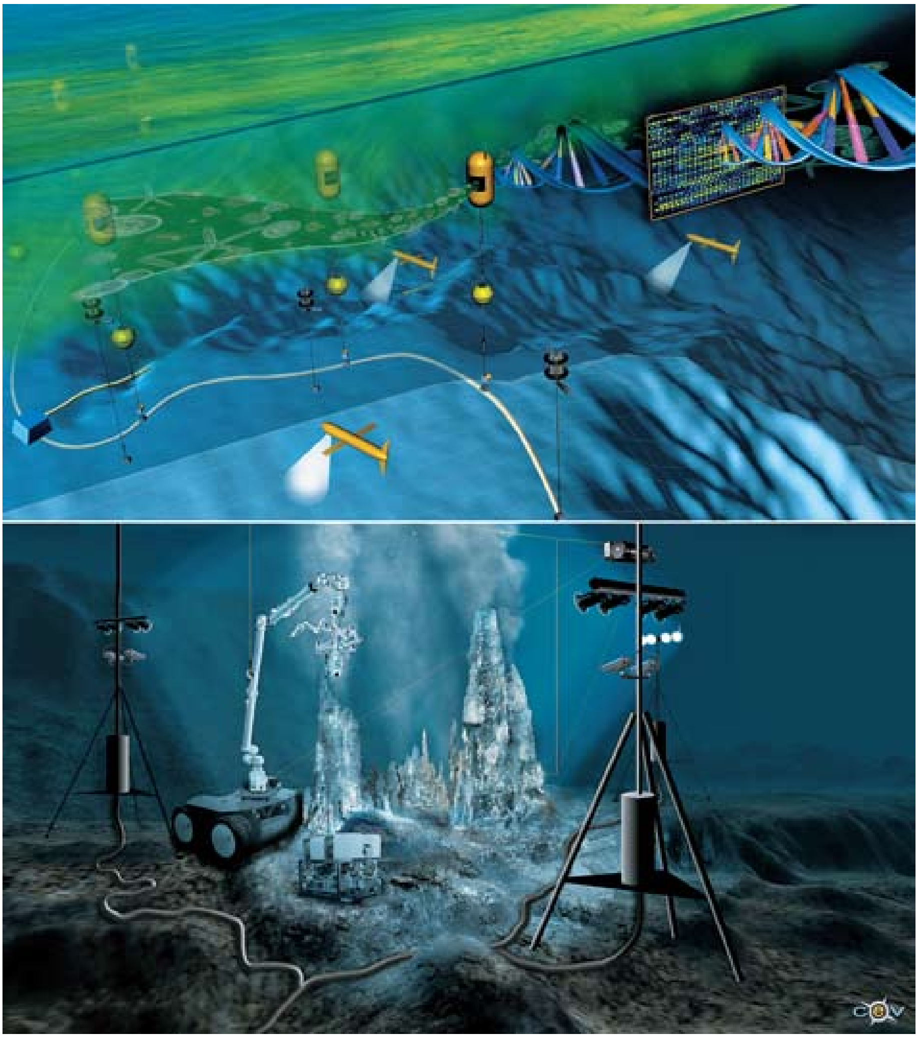

FIGURE 4.

Some of the transformative developments that could become routine within 5 years with the added power of a cabled support system. The top image shows miniaturized genomic analysis systems adapted from land laboratories to the ocean to allow scientists, with the flip of a switch in their lab hundreds of miles away, to sample ambient flow remotely and run in situ *gene sequencing operations within the ocean. The data can be made available on the Internet within minutes of the decision to sample microbes in an erupting submarine volcanic plume or a seasonally driven phytoplankton bloom. The lower part shows a conceptual illustration of an entire remote analytical-biological laboratory on the seafloor that allows a variety of key measurements or dissections to be made* in situ *using stereo high-definition video to guide high-precision remote manipulations.*

Scientific concepts by Ginger Armbrust and John Delaney; graphic design by Mark Stoermer for CEV.

in which scientists, engineers, and educators conduct their professional activities, the most far-reaching effects may be a significant shift in public attitudes toward the oceans as well as toward the scientific process. The real-time data and high-speed communications inherent in cabled remote observing systems will also open entirely new avenues for the public to interact with the natural world.

In the final analysis, having predictive models of how the ocean functions based on decades of refining sophisticated computer simulations against high-quality observations from distributed sensor networks will form the basis for learning to manage, or at least adapt to, the most powerful climate modulating system on the planet—the global ocean.

ACKNOWLEDGMENTS

We gratefully acknowledge the significant influence of Jim Gray, who unflinchingly stated that this cabled ocean observing approach using high-bandwidth and real-time data flow would be integral to human progress and understanding of the world we live in. We are also pleased to acknowledge the support of the University of Washington, the National Science Foundation, the Consortium for Ocean Leadership, and the Microsoft External Research group for technical collaboration and financial support. NSF and the National Oceanographic Partnership Program were particularly supportive of the early development of the NEPTUNE concept from 1998 to 2005, through grants to J. R. Delaney. Deborah Kelley, Nancy Penrose, and Mark Stoermer contributed significantly to the preparation of this manuscript and to conversations bearing on the content.

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