Director's Comments

Exploration of the oceans is poised to take a quantum leap befitting a new millennium. Advances in knowledge and technology will bring new understanding of our oceans—understanding that will be essential as we embark on an increasingly urgent societal mission.

Sixty years ago, with the world threatened by war, ocean scientists dove headlong into complex questions about the oceans and solved many that had important military ramifications. They played a big role in winning that war and also the subsequent Cold War. But the post-war surge in basic oceanographic research took us far beyond the arena of national security. It fundamentally transformed understanding of our planet—and life on it—by showing that the oceans constitute a critical component of a dynamic system that makes Earth uniquely habitable.

That system faces threats unprecedented in the history of humanity. Over the next 50 years, the world's population is expected to double—and to triple in coastal regions. Mounting stress on the oceans is already evident in the form of harmful algal blooms, beach erosion, coastal pollution, and declining coral reefs and fisheries. The population explosion also exposes more people to natural disasters, such as hurricanes, floods, droughts, forest fires, fishery collapses, famines, and epidemics. All these catastrophic scenarios hinge on the vicissitudes of climate—whose ultimate source and driver are the oceans.

To sustain our quality of life, we must protect, use, and manage the oceans wisely. We need to grasp how they work. The threats that humankind faces in the next half-century are different from those of decades past. But the stakes are high, and the world will need—and expect—the ocean science community to rise to the occasion and find creative solutions.

As in the past, the Woods Hole Oceanographic Institution is singularly positioned to do the important work at hand. Our critical mass of excellent scientists and engineers working synergistically, our access to the sea, our educational programs, our focus on the oceans, our history of success, and our worldwide reputation for interpreting and transitioning scientific information all make WHOI ideally suited to lead global efforts that will help make a difference.

Tom Kleindinst

British Deputy Prime Minister John Prescott is flanked during his April visit by WHOI Director Bob Gagosian and Emma Dieter, Program Manager for Ship Operations at the National Science Foundation. Prescott congratulated Deep Submergence Laboratory members, from left, Dana Yoerger, Tom Crook, P.J. Bernard, Will Sellers, Andy Bowen, Steve Lerner, Bob Elder, and Jon Howland on their survey of the sunken British vessel Derbyshire.

In 1999, the National Oceanic and Atmospheric Administration gave two of our scientists, Don Anderson and Peter Wiebe, its Environmental Hero Award for "tireless efforts to preserve and protect the nation's environment." Anderson, who held the Stanley W. Watson Chair from 1993 to 1998, developed the nation's first coordinated research efforts to understand and find remedies for harmful algal blooms (HABs). These sudden, rampant proliferations of single-celled organisms have serious deleterious impacts on coastal resources, regional economies, and public health, and they have been occurring with alarmingly greater frequency. Anderson's efforts to inform public officials, researchers, corporations, and health organizations about HABs led NOAA to call him "the nation's strongest voice on HAB."

Wiebe, who holds the Charles Adams Chair, was cited for leading the US Global Ocean Ecosystems Dynamics (GLOBEC) program to provide vital information on oceanic processes that control fish populations and lead to declining fish stocks. Since 1994, he has coordinated scientists, research programs, cruise schedules, and data management during investigations of the historically abundant fishing grounds on Georges Bank, and he is launching a pilot program to involve local fishermen as full partners in collecting oceanographic data to support fisheries research.

Both these scientists will tell you that their ability to take on leadership roles of ambitious research efforts was enhanced by being awarded endowed chairs at WHOI, which provided an invaluable measure of freedom from the relentless pressure of writing proposals to fund their research.

In 1999, we added another endowed chair in honor of Robert W. Morse, WHOI Scientist Emeritus, third dean of the MIT/WHOI Joint Program, and a founding director of Research Corporation Technologies, which supports commercial development of innovations from universities and research institutions worldwide. Research Corporation Technologies endowed the chair with funds from the Frederick Gardner Cottrell Foundation. The first Morse Chair holder is Hal Caswell, a leading mathematical ecologist who has developed widely used modeling techniques to study population dynamics. His 1999 study, which warned of a dangerous declining trend in the endangered northern right whale population, served as a wake-up call to launch renewed efforts to prevent the species' extinction.

Senior Scientist Robert Weller and Associate Scientist Steven Anderson received, respectively, the 1999 Secretary of the Navy/Chief of Naval Operations Oceanographic Research Chair and the Office of Naval Research/Institution Scholar award. Only two of each of these awards are given each year. Weller and Anderson plan to design, build, and deploy surface buoys equipped with meteorological and underwater sensors to track oceanic processes and air-sea interactions that influence Earth's climate. These buoys are among the instrumentation being developed for a proposed Global Ocean Observing System (GOOS). Weller is a leader in efforts to design and implement GOOS, while other WHOI scientists are helping to develop another component of the system: free-ranging floats that collect data on oceanic conditions and periodically transmit them to shore via satellites. GOOS offers the unprecedented potential to begin to define the ocean's role in shaping our climate and gives us the potential to predict (and prepare for) short-term climate changes, such as El Niño and the North Atlantic Oscillation.

To make GOOS a reality will require an ambitious, coordinated effort. To encourage the process, in 1999 I co-convened a meeting of international oceanographic institutions that resulted in the Partnership for Observations of the Global Oceans. Nationally, the Consortium for Oceanographic Research and Education, which I serve as chairman of the board, plays a similarly important role: coordinating efforts of 61 member institutions and combining their voices to educate policymakers and the general public about the payoffs of oceanographic research.

This Institution is sharing the excitement of exploration and emphasizing the importance of the oceans by collaborating on a new museum exhibit, "Extreme Deep: Mission to the Abyss," which highlights deep-sea discoveries and WHOI exploration vehicles. Extreme Deep debuted in 1999 at the Museum of Science in Boston and subsequently traveled to the Children's Museum of Indianapolis, on a scheduled five-year itinerary to science centers and museums nationwide.

Dan Fornari

National Science Foundation Director Rita Colwell jubilantly emerges from Alvin following an October 1999 dive. Sub pilot Steve Faluotico is at left.

In April, John Prescott, Deputy Prime Minister of Great Britain spent a day visiting WHOI. His mission was to personally thank WHOI for helping to determine the truth about *Derbyshire*, a 964-foot British ship that sank in a 1980 Pacific typhoon with 44 people aboard. Our Deep Submergence Laboratory team used its full suite of deep-sea exploration vehicles to search the wreckage of *Derbyshire* 2.6 miles below the sea surface, collecting evidence that determined why and how the ship sank. It was a milestone in marine forensics that offered insights into preventing other shipwrecks. Another result may be collaboration with British scientists to develop the next generation of *Jason,* the remotely operated vehicle that took part in the *Derbyshire* mission.

1999 also marked a milestone for our human-occupied submersible *Alvin*, which quietly but no less momentously celebrated its 35th birthday, averaging about 100 dives per year in the service of science. The year also saw the arrival of our new Director of Development, Dan Stuermer, a graduate of the MIT/WHOI Joint Program. His careers as scientist, businessman, and corporate executive give him wide-ranging experience to spearhead efforts to raise the private funds needed to complement government funding.

The year also marked a significant loss for us at Woods Hole. Charley Hollister, who had been associated with WHOI since 1967 as scientist, Joint Program dean, and vice president of the WHOI Corporation, died August 23 in a hiking accident in Wyoming. Two endowed funds were established in his honor to support two of his greatest interests: watching students grow to become first-rate oceanographers, and pushing the envelope scientifically. The Charles D. Hollister Graduate Student Fellowship Fund will support budding oceanographers and the Charles D. Hollister Endowed Fund for Support of Innovative Research will provide research funds for risky ventures that federal agencies are too conservative to support.

Charley was a graduate student in the 1960s when plate tectonics revolutionized our understanding of the earth. How he would have enjoyed witnessing the next great leap in understanding, which I believe is just over the horizon.

—Robert B. Gagosian, Director

Comments from the Director of Research

One of the most significant events for WHOI in 1999 was the review of our scientific departments by Visiting Committees. We invited distinguished scientists from other institutions and members of our own Board of Trustees to give us an objective appraisal of the accomplishments and future directions of the departments. This practice, used by many other academic institutions, provides advice that we find invaluable in our own assessments and planning for future staffing, scientific activities, and infrastructure. We were pleased that the Visiting Committees found that WHOI continues to be healthy, that the quality of the scientific research and engineering is of world class caliber, and that our staff of scientists, engineers, and support personnel is well equipped to meet the future challenges of oceanographic research.

Many of the interesting and important problems in the ocean sciences lie close to the boundaries between the traditional disciplines. For example, understanding the structure of the ecosystem on Georges Bank, and ecosystems in general, involves the relationships between the seasonally varying and wind-induced currents and water masses and the distributions of larvae, prey, and other components of the ecosystem. Similarly, understanding and predicting sediment and sand transport along the coast requires an understanding of the interaction of waves and wind-induced currents, along with the turbulence along the interface between the sediment and the water.

The five scientific departments now overlap scientific interests and disciplines in many ways. Consequently, the 1999 evaluation was done by three separate committees, one to review the Geology & Geochemistry and Marine Chemistry & Geochemistry Departments, one to review the Physical Oceanography and Applied Ocean Physics & Engineering Departments, and the third to review the Biology Department. We asked the Visiting Committees to evaluate more than one department specifically to review the ways that the department staffs interact and to provide suggestions for ways to improve their collaborations for interdisciplinary research. Future funding from many of our traditional as well as new sources will place an increasingly important emphasis on interdisciplinary investigations. It is important that we insure that our structure does not impede the formation of teams that cross department boundaries. The Visiting Committees provided excellent feedback and suggestions in this area, as well as others. We are in the process of reviewing the reports in detail, finalizing the departmental responses to the Visiting Committee reports and have already implemented some of the recommended actions. We are grateful for the time and thoughtful effort Visiting Committee members (listed in the box) invested in their reviews of our departments.

Dave Gray

Senior Associate Director Jim Luyten, right, describes a temperature and salinity measuring device called a SEACAT to Dave Burnell of the US Office of Management and Budget, who visited WHOI in August1999.

—James R. Luyten, Senior Associate Director and Director of Research

1999 Visiting Committees

Applied Ocean Physics & Engineering and Physical Oceanography Departments

Arnold Gordon (Chair)
Physical Oceanography Program Leader, Lamont-Doherty Earth Observatory, Columbia University

John S. Allen
College of Oceanic & Atmospheric Sciences, Oregon State University

Philip W. Cheney
WHOI Corporation Member, Raytheon Company, Lexington, MA

Stanley E. Dunn
Chair, Department of Ocean Engineering, Florida Atlantic University

Alexander E. Hay
Department of Oceanography, Dalhousie University

William A. Kuperman
Director, Marine Physical Laboratory, Scripps Institution of Oceanography

William Large
Deputy Head of Oceanography Section for the Climate and Global Dynamics Division, National Center for Atmospheric Research

John M. Stewart
WHOI Trustee, McKinsey & Co., Inc., New York, NY

Biology Department

Bess B. Ward (Chair)
Department of Geosciences, Princeton University

Joseph S. Barr, Jr.
WHOI Corporation Member, Orthopedic Associates, Boston, MA

Sallie W. Chisholm
Civil and Environmental Engineering Department, Massachusetts Institute of Technology

Michael Gallo
Director, Environmental & Occupational Health Sciences Center, University of Medicine and Dentistry of New Jersey–Robert Wood Johnson Medical School

Michael M. Mullin
Director, Marine Life Research Group, Scripps Institution of Oceanography

Marine Chemistry & Geochemistry and Geology & Geophysics Departments

Christopher S. Martens (Chair)
Department of Marine Sciences, University of North Carolina-Chapel Hill

Kenneth W. Bruland
Ocean Sciences Department, University of California-Santa Cruz

Donald W. Forsyth
Department of Geological Sciences, Brown University

Alex N. Halliday
Department of Earth Sciences, Institute of Isotope Geology & Mineral Resources, Eidgenössische Technische Hochschule, Zurich, Switzerland

Charles Langmuir
Geochemistry Department, Lamont-Doherty Earth Observatory, Columbia University

Theodore C. Moore, Jr.
Director, Center for Great Lakes and Aquatic Sciences, University of Michigan

John J. Wise
WHOI Trustee, Mobil Technical Center, Paulsboro, NJ

Monthly listings of Institution-authored scientific publications can be found on the World Wide Web at: www.whoi.edu/science/publications.html.

Applied Ocean Physics & Engineering Department

The Applied Ocean Physics & Engineering (AOP&E) Department, with 138 staff members, 26 students, and 45 postdoctoral, guest, and visiting investigators, and a number of guest students, continues to make significant advances spanning diverse areas in ocean science, technology, and engineering research. In 1999, 42 principal investigators led 130 projects.

Ocean science research ranged from air-sea interaction and various mixing processes to sediment transport and benthic biology, and included acoustical oceanography, estuarine and coastal hydrodynamics, internal waves, physical-biological interactions, and surf and swash zone processes. In the technology category, AOP&E staff are developing a wide variety of ocean sensors as well as data acquisition and telemetry systems. They continue to develop or enhance various sensor platforms, including bottom-mounted systems and moorings as well as submersible, autonomous, and remotely operated underwater vehicles. Engineering research encompasses signal processing, underwater communication, autonomous vehicle control theory, image analysis, hydrodynamic modeling of vehicles and cables, dynamics of moorings, and fish propulsion.

There were a number of promotions this year including Jim Edson and Tim Duda to Associate Scientist with Tenure, Dennis McGillicuddy to Associate Scientist, and Lee Freitag to Senior Engineer. Ken Foote, an expert in fisheries acoustics, formerly at the Institute of Marine Research in Bergen, Norway, was appointed Senior Scientist, and two surf and swash zone specialists joined the staff: Steve Elgar, formerly at Washington State University, was named Senior Scientist. Britt Raubenheimer was appointed Assistant Scientist following completion of a postdoctoral position at the Scripps Institution of Oceanography. Also, Bill Carey, Professor at Boston University and expert in acoustic signal processing, became an Adjunct Scientist, and Neil Brown was appointed Oceanographer Emeritus.

Susan Green, Scripps Institution of Oceanography

Steve Elgar and Britt Raubenheimer are among the silhouetted figures carrying a frame with instruments that were used to measure surf and swash zone waves, currents, and sand levels near the Scripps pier in La Jolla, California.

AOP&E staff who were formally recognized for their accomplishments include Andy Bowen and Keith von der Heydt who each received Senior Technical Staff Awards, Jim Preisig who received an Office of Naval Research Young Faculty Award in the Special Research Program in Ocean Acoustics, and Wade McGillis who was named a fellow of the NOAA/University of Miami Cooperative Institute for Marine and Atmospheric Studies.

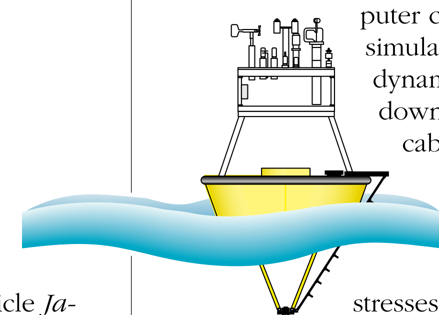
—Timothy K. Stanton, Department Chair

Fishing for Solutions to Cable Problems

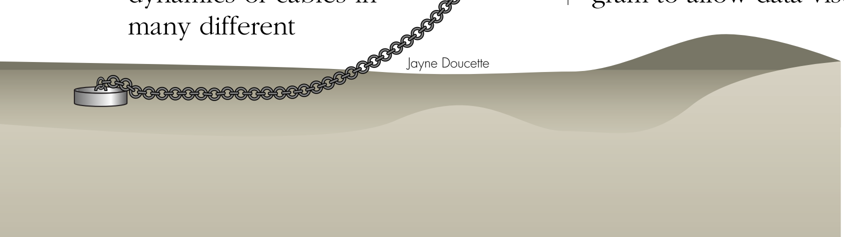
Mark A. Grosenbaugh
Associate Scientist

What do oceanographic moorings, the remotely operated vehicle *Jason*, and fly fishing have in common? They all depend on the performance of flexible cables. For oceanographic moorings, the cables can be made of heavy chain in order to resist high tensions caused by buoy motion and friction due to the cables rubbing on the sea bottom. Tethers for underwater vehicles, on the other hand, are neutrally buoyant and have very low tensions in order to uncouple ship motions from the vehicles. In fly fishing, the shape of the fly line requires careful control to assure proper presentation of the artificial fly. Poor technique with the fly rod can result in knots forming in the line or, worse, the formation of a shock wave that snaps the fly off the end.

Joint Program student Jason Gobat and I are trying to learn more about these and other cable systems through numerical simulations and have developed a software package for predicting the dynamics of cables in many different configurations and applications. The program, called *WHOI Cable*, is unique in its ability to calculate the dynamics of cables even when the tension goes to zero. Most computer codes that simulate cable dynamics break down if the cable tension vanishes. By including bending stresses in the equations of motion, we are able to remove this singularity and continue the simulation. We can even simulate an ROV tether wrapping around itself. Someday, we hope to be able to simulate the formation of knots.



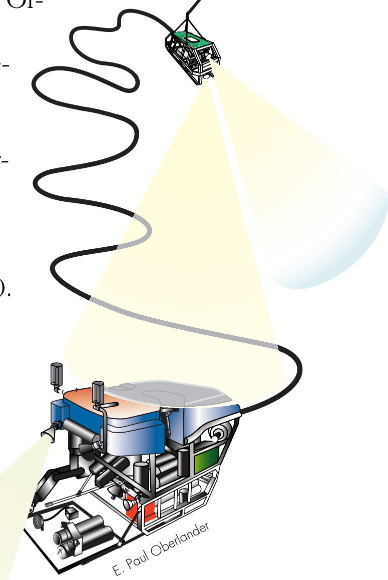
Another unique capability of *WHOI Cable* is its ease of use. Our user interface makes it simple to enter numerical parameters, material constants, the system layout, and the environmental conditions. Another interface allows the user to track the progress of the computation with the option of changing the numerical parameters manually or letting the simulation optimize performance automatically. Graphic capabilities are built into the program to allow data visualization even while computation proceeds.



The output can also be downloaded and viewed by any number of mathematical analysis programs. So far, more than 30 different organizations in eight different countries are using *WHOI Cable*.

We continue to update the software as we encounter challenging cable problems that require special treatment. Who knows—someday we may even be able to help a fisherman cast the extra distance that makes the difference between catching and not catching a prized trout.

The development of *WHOI Cable* was supported by a grant from the Office of Naval Research (Ocean Engineering and Marine Systems Program).



Research on flexible cables benefits a range of oceanographic instruments as well as fly fishermen.

Photomosaicing Underwater Images Sheds Light on the Deep Ocean

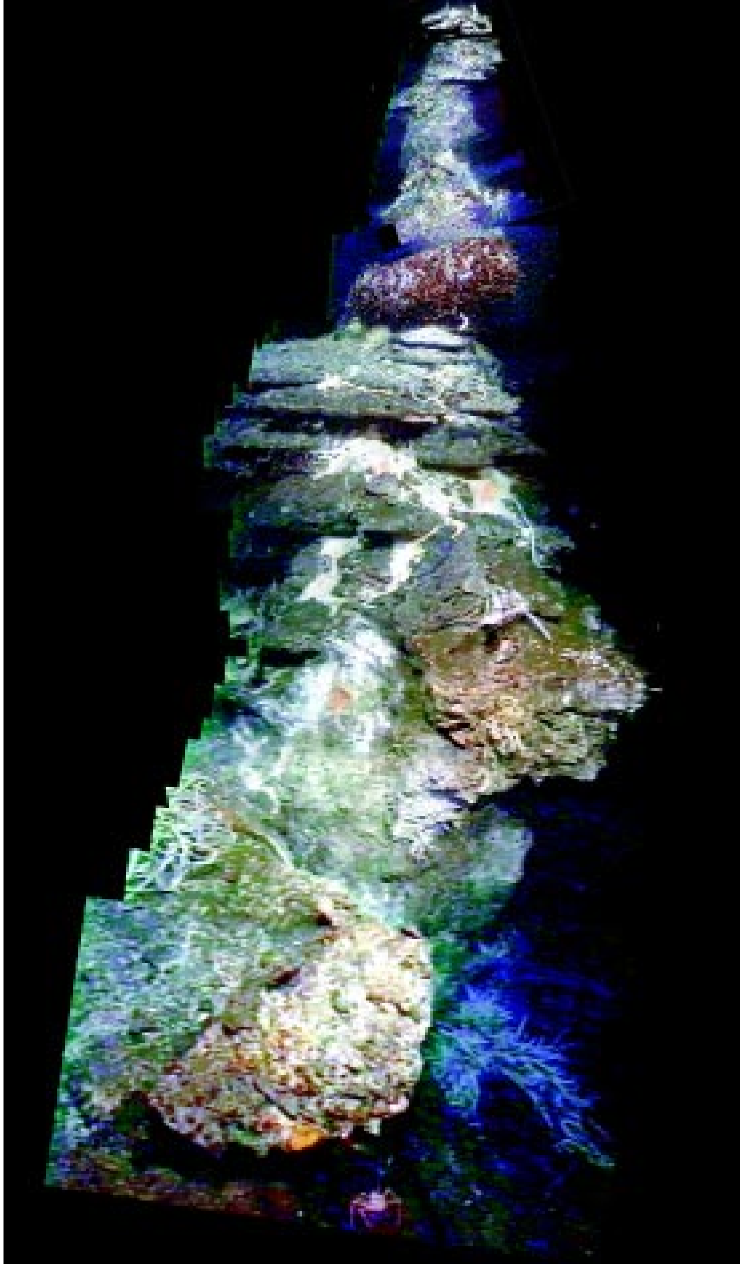
Hanumant Singh
Assistant Scientist

One of the fundamental problems with working underwater is that the electromagnetic spectrum (including visible light) attenuates extremely rapidly and nonlinearly. From a practical imaging standpoint, this means that large objects cannot be framed within a video or other optical camera's field of view. Thus obtaining a global perspective of a site of interest on the seafloor—an archeological find (box opposite), a geological channel, a hydrothermal vent (figure at right), the debris field associated with a plane crash, or the remains of a whale carcass (below)—requires piecing together a series of images in a process called photomosaicing. This involves running a carefully planned survey over the site, collecting a series of overlapping images, identifying common features in the overlapping imagery, and then merging the images to form strips, which are then assembled into larger mosaics.

Several factors make this a hard problem. There may be constraints on the way underwater vehicles can perform surveys due to insufficient accuracy in small-area navigation and a lack of mechanisms to automatically control the vehicle. Physical constraints on the distance separating cameras and lights as well as constraints on the energy available for operating the lights also constitute major impediments. Finally, and most important, the unstructured nature of the underwater terrain introduces incremental distortions into the photomosaic as successive images are added in.

One objective of scientists, engineers, and graduate students at the Deep Submergence Laboratory is to develop a key set of capabilities for mosaicing using a variety of platforms. Those we work with include the WHOI-operated, human-occupied submersible *Alvin*, remotely operated vehicle *Jason*, and autonomous underwater vehicle *ABE*, as well as the US Navy's *NR-1* submarine. Our funding sources include the Office of Naval Research, the National Science Foundation, and WHOI Assistant Scientist support from the Penzance Endowed Fund, the John P. Chase Memorial Endowed Fund in Support of Scientific Staff, and David G. Mugar.

We are focusing on bounding the errors in the photomosaics to enable quantitative measurements (for example, the size of amphorae). Two important issues here are the roles of navigation and of multisensor information. Traditional acoustic navigation can be used to limit the error in the photomosaics while the image registration inherent in photomosaicing can be used to complement and thus yield more



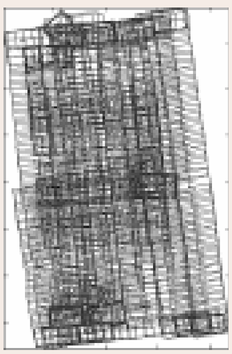
A 53-image color photomosaic depicts a hydrothermal vent located in the Sea of Cortez in Baja California. (Chief Scientist: Dana Yoerger, WHOI)

The remains of a whale off of the coast of San Diego was imaged from the human-occupied submersible Alvin. *(Chief Scientist: Craig Smith, University of Hawaii)* accurate navigation estimates of the vehicle. The fusion of multisensor information, in our case high resolution bathymetric measurements, provides three-dimensional information that can be used to rid photomosaicing of the primary source of error, terrain effects.

Eventually we hope to build seamless quantitative photomosaics of sites repeatedly over time to enable us to detect spatial and temporal changes in the context of deep ocean mapping exercises.

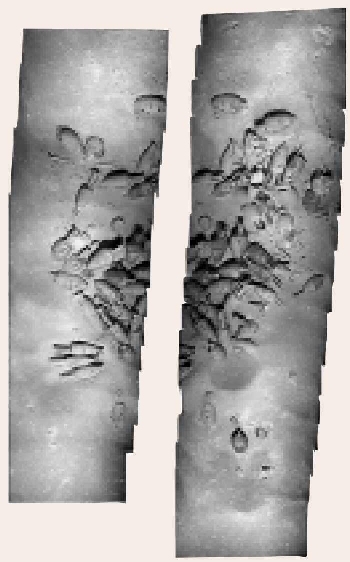
The Process of Photomosaicing

The site of interest is a Roman shipwreck located at 800 meters depth in the Skerki bank area off Sicily in the Mediterranean Sea. This site was imaged with the remotely operated vehicle *Jason*. (Chief Scientist: Robert Ballard, WHOI)



Step 1 *Vehicle operators conduct a carefully planned survey over the area of interest to ensure sufficient coverage and overlap in the imagery. Image footprints are projected on the area of interest to allow operators to choose individual images for use in the mosaic.*

Step 2 *Individual images are processed to remove lighting and other artifacts. These images are then merged into single strip mosaics by indentifying common features in successive images.*



Step 3 *Individual strips are then mosaiced together using a technique similar to that used in Step 2.*

Step 4 *Ongoing work focuses on understanding and improving the quantitative nature of the mosaicing process.*

New Measurements Reveal Dynamics of Wave-Driven Currents

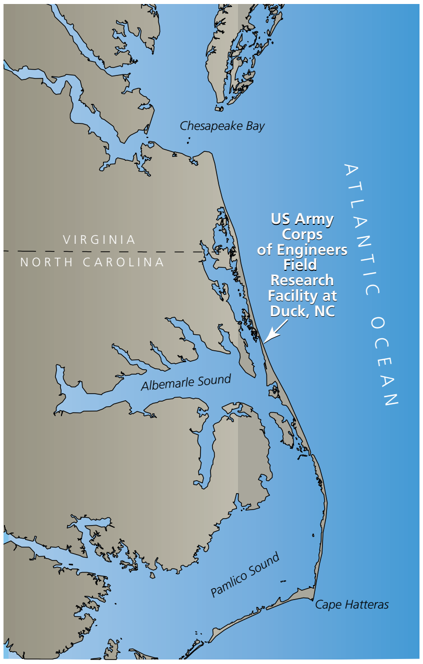
John H. Trowbridge
Associate Scientist

Breaking waves on beaches drive alongshore currents that reach or exceed one meter per second, among the fastest oceanic flows. These currents are important because they produce the so-called coastal "river of sand," typically transporting hundreds of thousands of cubic yards of beach material alongshore past any given point each year, with the potential for dramatic coastal erosion or accretion. Wave-driven currents on beaches are also important in military operations and because they transport and disperse pollutants.

Rebecca Beavers, Duke University

This 35-foot-tall motorized Coastal Research Amphibious Buggy or CRAB assists researchers working in nearshore waters at the US Army Corps of Engineers Field Research Facility in Duck, North Carolina.

Although the wave-induced driving mechanism has been known for 30 years, the processes that counter the effects of breaking waves, permitting a "force balance" that controls the magnitude and distribution of wave-driven currents, have remained obscure. Most researchers argue that the dominant effect balancing the wave-induced forcing is drag on the seafloor. They further argue that this drag force is transmitted throughout the water column by turbulent eddies, which are far weaker than either the breaking waves or the alongshore currents,



but are nevertheless an effective agent for transmitting drag. Although the vertical transport of drag by turbulence is an essential element of conceptual and quantitative models of surf-zone processes, it has never been measured directly, because instrumentation and methods of analysis sufficient to extract the small velocities produced by turbulence from the much larger signals produced by waves and currents have not existed.

Recently, however, I developed a new technique for extracting effects of turbulence from measurements dominated by waves and currents. This method was applied in the 1997 "SandyDuck" field program, a multi-investigator, multi-institution experiment located at the US Army Corps of Engineers Field Research Facility in Duck, North Carolina. An array of five high-quality acoustic velocity sensors, recently made available by SonTek, Inc., San Diego, California, was deployed on a bottom-mounted steel frame at a water depth of five meters. During the three-month measurement period, three instruments were damaged badly, probably by logs or other semi-submerged objects carried by strong storm-driven flows, and severe fouling occurred late in the experiment. However, the remaining two sensors produced measurements sufficient to provide estimates of the force-transmitting role of turbulence during three large storms. Measurements obtained by other SandyDuck investigators, notably AOP&E Department members Steve Elgar and Jim Edson, provide estimates of wave and wind forcing, which are required to put the turbulence measurements in context.


Don Peters

This array of five acoustic velocity sensors was placed five meters deep for studies of the vertical transport of drag by turbulence.

The results are surprising. Although measurements during fair conditions with small waves are consistent with expectations based on previous studies, measurements during large waves indicate a relationship between turbulence and the alongshore current that differs dramatically from theoretical predictions. Energy dissipation associated with breaking did not have a large signature near the seafloor, contrary to expectations, and the drag force inferred from the turbulence measurements was only about half the value required to balance the wind and wave forcing. We are working to understand these results and planning future measurements that will clarify their generality and proper interpretation.

Funding for the measurements was provided by the Mellon Foundation and the Rinehart Coastal Research Center. Funding for the analysis was provided by the National Science Foundation. Janet Fredericks expedited the measurements and carried out the preliminary analysis.


Janet Fredericks

This is the frame above three months later. Despite severe fouling and serious damage to three of the instruments, the two operational sensors provided sufficient measurements to estimate the force-transmitting role of turbulence during three large storms.

Biology Department

Biology is a diverse field, and research in this department touches on almost all aspects of life in the sea. During 1999, WHOI biologists worked on everything from viruses to whales, using a range of powerful field and laboratory instruments and approaches including molecular techniques, video microscopy, flow cytometry, integrated acoustic and optical field sampling instruments, behavioral observations, and mathematical modeling and analysis. This work took place in the local waters of New England, and further afield in the Atlantic, Pacific, and southern oceans.

WHOI maintains an especially strong reputation in many areas of biological oceanography. These include the ecology and physiology of bacteria and protozoa; bio-optical studies of phytoplankton; advanced optical and acoustic techniques for zooplankton distribution and behavior; the ecology, behavior, and development of invertebrate larvae; mathematical analysis and computer modeling of life history, population dynamics, and physical-biological interactions; toxicological and molecular research on how pollution affects marine organisms; and acoustical, anatomical, and behavioral studies of marine mammals.

As availability of federal research support has tightened, our scientists have turned to diverse sources of support–local, state, federal, international, corporate, and private agencies and foundations. Altogether, department investigators submitted 150 proposals to these sources, and received full or partial funding for 43 percent of them, totaling a little over $5 million for sponsored research in 1999. In addition to their individual research programs, the staff continues to participate and provide leadership in large national and international programs, including the Joint Global Ocean Flux Study research in the Atlantic and southern oceans and the Ridge Inter-Disciplinary Global Experiments and Larvae at Ridge Vents Program for hydrothermal vents. Both the National Ecology and Oceanography of Harmful Algal Blooms Program for red tide research and the US Global Ecosystems Dynamics Northwest Atlantic Program on Georges Bank have their headquarters in the WHOI Biology Department.

Scientists and crew aboard R/V Oceanus prepare to launch a Multiple Opening/Closing Net/Environmental Sensing System during the final year of Georges Bank fieldwork for the Global Ocean Ecosystems Dynamics program.

At the close of 1999 the department had 24 Scientific Staff, along with 7 Scientists Emeritus, 3 Oceanographers Emeritus, 17 Postdoctoral Scholars, Fellows, and Investigators, 16 Technical Staff, 36 Joint Program students, and 33 other support staff. During the year, the Scientific Staff pursued over 140 separate research projects, publishing 67 scientific papers and books.

Cabell Davis and Peter Tyack were promoted to Senior Scientist, Mark Hahn was awarded tenure, and Heidi Sosik was promoted to Associate Scientist. On the Technical Staff, Carl Wirsen was promoted to Senior Research Specialist and Steve Molyneaux to Research Associate II, Freddy Valois became our third Oceanographer Emeritus, and Jim Craddock retired. We were sorry to lose Senior Scientist David Caron to the University of Southern California, but grateful for the stellar career he had built in our department.

National honors went to Senior Scientists Don Anderson and Peter Wiebe, recognized by the National Oceanic and Atmospheric Administration as National Environmental Heroes. Senior Scientist John Stegeman received an Award for Extraordinary Service to the National Research Council, and Scientist Emeritus John Teal was honored with the Odum Award and the National Wetlands Award. Senior Scientist Hal Caswell was the first recipient of the Institution's new Robert W. Morse Chair.

—Laurence P. Madin, Department Chair

Antarctic Studies Illuminate Diversity in Extreme Environments

Rebecca Gast
Assistant Scientist

Mark Dennett

Rebecca Gast and Robert Sanders (Temple University) collect slush samples during 1999 Antarctic investigations.

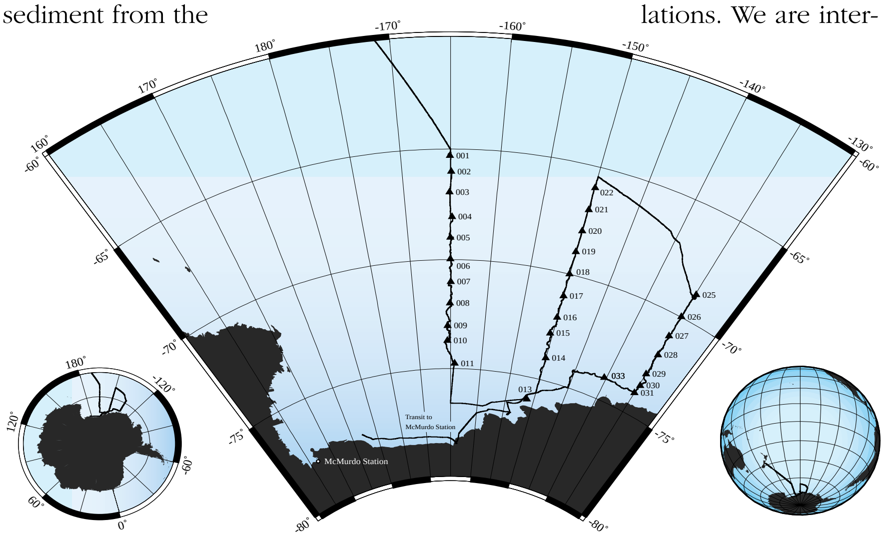
Human fascination with the top few hundred meters of water in tropical and temperate locations leads us to view the ocean as a relatively warm body of water. However, much of the ocean is actually characterized by extremely cold temperatures—below the warm surface layer, water temperatures average 3˚C, while at high latitudes and great depths, the temperature is permanently less than 1 to 2˚C. Nevertheless, the vast majority of information on the growth and production of marine organisms pertains to those living in the warm surface water of tropical and temperate climates.

Along with David Caron (University of Southern California), Mark Dennett and I are addressing fundamental gaps in our knowledge about growth and productivity in extreme cold water ecosystems. With funding from the National Science Foundation (NSF) Life in Extreme Environments program, we are studying the diversity and physiology of protists (nonbacterial, single-celled organisms such as algae) in samples of water, ice, slush, and sediment from the Ross Sea, Antarctica. We collected our samples while aboard the ice-breaking research vessel *Nathaniel B. Palmer* from December 26, 1998, through February 4, 1999.

Interest in microbial diversity has risen considerably in recent years, primarily due to the application of molecular biological approaches that allow scientists to identify species of organisms so small that they lack taxonomic characteristics useful for identification. These methods help us answer questions about the diversity and biogeography of microbial eukaryote (protist) populations. We are interested in the diversity of small protists (algae and protozoa less than 100 microns) because of their fundamental roles in aquatic food webs as producers and processers of carbon. Photosynthetic protists (algae) form part of the base of the food web, and the protozoa are primary consumers of picoplanktonic algae (less than 10 microns) and bacteria. Thus both move carbon upwards through the food chain.

Microbial eukaryotes are essential in most, if not all, ecosystems, and extremely cold environments are no exception. Though it seems likely that the very low temperatures of these environments would significantly decrease the physiological functioning of the organisms, this appears not to be the case. Protist populations are quite healthy and grow quite well in the ice, slush, and water of the Ross Sea.

Our analysis of the genetic diversity of Ross Sea protists targets the small subunit ribosomal RNA genes (srDNA) in order to determine phylogenetic relationships by comparison with sequences in an srDNA database. This allows us to ascertain whether the organism we are examining is related to any already known, or whether it is novel. In our research we have come across



Cruse track triangles indicate stations where water, ice, and slush were sampled from the research vessel/icebreaker Nathaniel B. Palmer *(National Science Foundation).*

both known and novel sequences that correspond to diatoms, dinoflagellates, ciliates, flagellates, and even some amoebalike organisms. We have also determined that different sample types (such as those from water and ice) rarely share the same sequence types, even when collected at the same location. In an analysis of 300 sequences obtained from water, ice, and slush at a single station, only one srDNA sequence was shared by all three sample types, suggesting adaptation of specific organisms for these specialized environments.

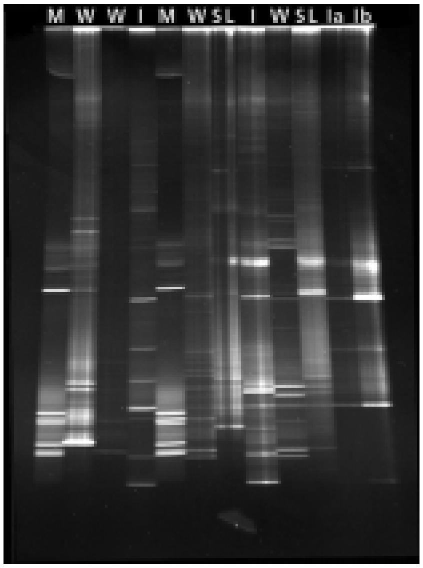
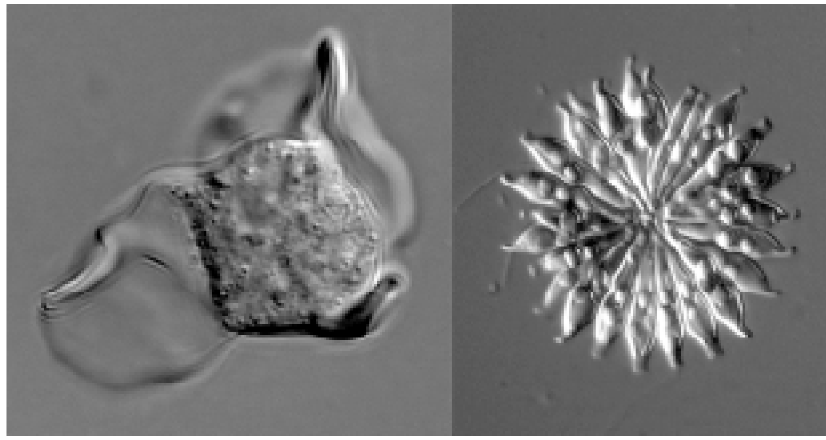


Image of gel showing genetic diversity of different water, ice, and slush samples along with a marker (M) used to orient and compare gels.

When culturing organisms from extreme environments, it can be very difficult to obtain those representative of the original population. This is due to problems in accurately replicating and maintaining important environmental features, such as pressure or temperature, during collection and enrichment. In our work to obtain protistan cultures from Antarctica, we have been extremely careful to keep the organisms at 0 to 2°C at all times. This has allowed us to recover an extensive collection of protists that exhibit sensitivity to temperatures higher than 4°C, and potentially represent truly psychrophilic organisms. We are now beginning to look at the srDNA from our cultures to determine whether the organisms we have grown are representative of the predominant organisms in the original samples. If they are, we will target them for physiological studies to determine how these organisms have adapted for growth in the extreme cold. We have also begun to design oligonucleotide probes that can be used directly on environmental samples to detect and quantify the abundance of a particular protist. This will allow us to track its changes in the natural population over time and determine what role it plays in the community.



More than 200 antarctic cultures Gast and colleagues are studying include the amoeba at left and the cluster of diatoms at right. Both are approximately 50 microns in size.

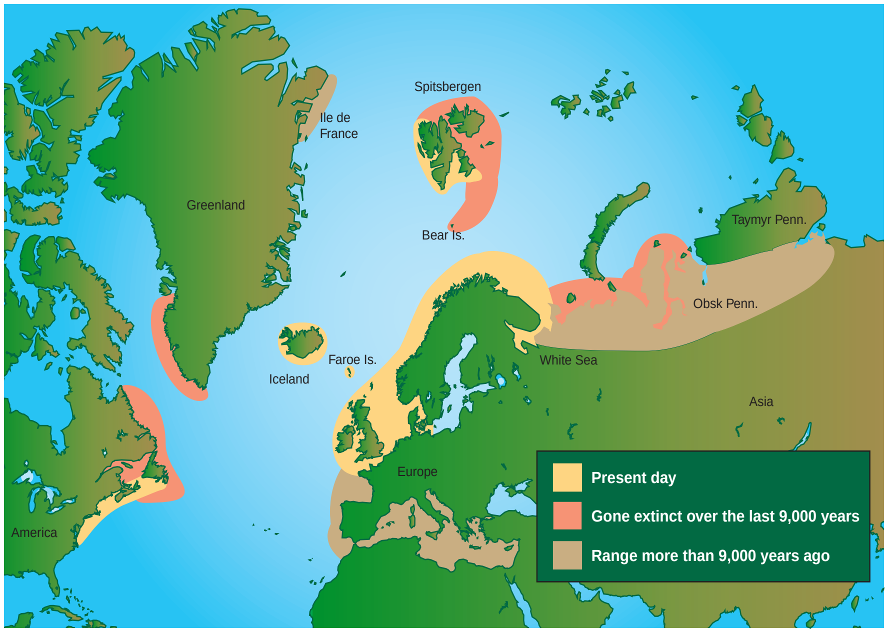
Genetics, Climate, and Commercial Fisheries

Kenneth Halanych
Assistant Scientist

The distributions of species throughout the world's oceans are largely influenced by temperature regimes. Thus, changes in global climate can cause shifts in species distributions, creating genetic signatures representative of biogeographic history. For example, several species of marine intertidal invertebrates display reduced genetic diversity in the northwest Atlantic due to reduced habitat size and availability during the last glacial maximum. In other words, glaciers reduced the effective population size of shallow near-shore species, allowing evolutionary forces (such as genetic drift and extinction) to produce a characteristic genetic signature. By studying the genetic diversity and structure within and between different organismal populations, it is possible not only to explore the interface of environmental influences and evolutionary history, but also to begin to formulate predictions of how human-induced global climate change will impact the future distributions of marine species.

In the ocean quahog, *Arctica islandica*, both recent molecular genetic data and paleontological information suggest that global changes in ocean water temperature have caused dynamic shifts in this clam's distribution over time. Because the ocean quahog is the basis of an international multi-million dollar industry (it is the main ingredient of clam chowder), this finding relates human-influenced climate change to future viability of commercial fisheries. We used molecular tools to identify genetic boundaries within the species and to assess levels of genetic diversity. This information should allow the parameters and assumptions employed in models of sustainable yield to be refined, and thus aid future management of this species.

Contrary to the commonly accepted idea regarding reduced genetic diversity in the northern extent of North Atlantic invertebrates, in the ocean quahog higher genetic diversity is observed in northern localities (Nova Scotia and Iceland) than in southern areas (Mid-Atlantic Bight). Inspection of the fossil record reveals the northern range of the ocean quahog was considerably larger during the most recent climatic optimum, or warm period, that ranged from 8,400 to 4,900 years ago. This may have maintained or promoted higher genetic diversity through a greater habitat availability as well as larger population size. Limited diversity was also noted south of Cape Cod, a region known to have experienced significantly elevated temperatures during the climatic optimum. Presumably, the ocean quahog went extinct in the warmer waters, and has only recently recolonized after ocean water temperatures cooled down (about 2,000 to 4,000 years ago).



Jack Cook

The biogeographic distribution of the ocean quahog, Arctica islandica, *since the last glacial maximum.*

Clearly, global climate change can effect large-scale changes in the distribution of at least some commercially important species. Based on molecular and paleontological data, the continued trend of human-induced global warming suggests that populations of *Arctica islandica* south of Cape Cod (the largest ocean quahog fishery) are at serious risk. However, the genetic structure of more species (both shallow and deep water) must be explored before generalizations can be made about the interaction of global climate change and species distributions. While advances in biotechnology offer powerful tools with incredible resolving capabilities for genetic questions, effort and funding must also focus on sampling current populations so that future trends can be predicted.

This research represents a collaborative effort with the National Marine Fisheries Service (primarily James R. Weinberg), and was sponsored by the Rinehart Coastal Research Center and the Sweden-America Foundation (support to Thomas Dahlgren).

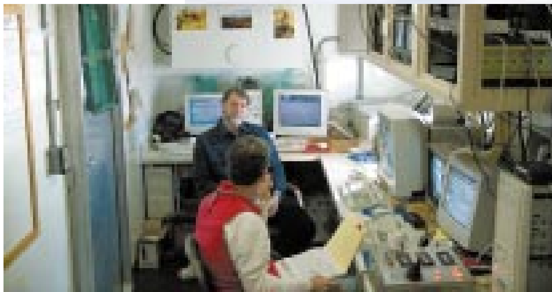
BIOMAPER II: New Capability for the New Millennium

Peter H. Wiebe
Senior Scientist

Oceanography, at its core, is an observational science. Measurements of seawater properties and of plant and animal distribution, abundance, and rate processes (for example feeding, growth, death) form the building blocks, the data, from which our understanding of how the ocean's physical, chemical, biological, and geological systems work. The vastness of the world's ocean, however, makes it difficult to gather enough observations to adequately characterize or describe the phenomena we study.

During the 20th century, the mainstay of programs designed to study the ocean interior were observations from research vessels often made at widely separated station locations. The rich variation in abundance of marine animal and plant species on spatial scales from centimeters to thousands of kilometers and the sparseness of sampling stations have resulted in gross undersampling of ocean phenomena. Only in the last decade or so has technology begun to overcome this fundamental impediment, enabling development of towed vehicles that can be deployed between stations to fill the data gaps. The relevant technological advances include high-speed computers, towing cables with optical fibers (for high-speed, high-bandwidth, two-way data communication), as well as electrical conductors (for power), and an impressive array of acoustic, optical, and physical sensors.

On the leading edge of such developments is the BIo-Optical Multi-frequency Acoustical and Physical Environmental Recorder, also known as BIOMAPER II. Following on the heels of its prototype (BIOMAPER), it was specifi-



Mark Benfield

Peter Wiebe

Instrument losses inspired a new approach to BIOMAPER II operations. This substantial Dynacon winch and handling system provides easier handling of the one-ton instrument as well as extended operation in storm conditions. The inset shows Peter Wiebe (top) and Chuck Greene (Cornell University) in the portable van specially outfitted for command and control of BIOMAPER II.

cally developed in 1996 with a grant from the Office of Naval Research to conduct high speed, large area surveys of zooplankton and environmental property distributions. It has since been used on a number of test and scientific cruises to the Gulf of Maine and Georges Bank as part of the US Global Ocean Ecosystems Dynamics (GLOBEC) Northwest Atlantic/ Georges Bank Study.

The vehicle usually is towed from the starboard side of medium sized oceanographic research vessels, such as R/V *Oceanus*. It is generally operated over a wide range of towing speeds from 0 to 10 knots. Most scientific missions require operations in a "tow-yo" pattern: The winch operator constantly spools tether out, then in, so the vehicle travels up and down through the entire water column in a slow zigzag fashion. The maximum operating depth of the system is 500 meters, and average tow speed is four to six knots, depending on the depth of the vehicle.

The 3.78-meter vehicle has a free-flooded, open-frame architecture with an outer skin in the form of easily removable flat plastic panels. It weighs approximately 2,000 pounds in air and 1,200 pounds in water. It is equipped with a multi-frequency sonar (uplooking and downlooking pairs of transducers operating at five frequencies: 43, 120, 200, 420, and 1,000 kilohertz), a video plankton recorder system (VPR), an environmental sensor package (conductivity/temperature/ depth device, fluorometer, transmissometer), and several other bio-optical sensors including down- and upwelling spectral radiometers and spectrally matched attenuation and absorption meters. A 20-foot shipping container van, specifically modified to become the at-sea laboratory space for command and control of BIOMAPER II, holds the electronic equipment for real-time data processing and analysis.

Towed instruments are susceptible to the same weather constraints as any other kind of over-the-side instrument package, notably difficulties that arise in deployment or recovery operations during high sea states. Usually, when the winds blow at 25 to 30 knots or higher for a sustained period, work at sea becomes impaired or impossible. A second grant from ONR enabled purchase of a unique self-contained winch with 1,000 meters of electro-optical cable, slack tensioner, and an overboard handling system built by Dynacon Inc. to enhance BIOMAPER II performance in high sea states. The system is powered and controlled electrically, and driven hydraulically. The winch, slack tensioner, and overboarding J-frame assembly were installed on R/V *Endeavor* (University of Rhode Island) and successfully used with BIOMAPER II on two late 1999 Gulf of Maine cruises. During an October cruise, a powerful gale (with wind gusts to 55 knots and sustained winds often over 40 knots) set upon *Endeavor* and raged for more than a day while BIOMAPER II was deployed. Wire tension records demonstrate the substantial protection the slack tensioner system provided against excessive shock loading of the cable and the vehicle in high sea states. BIOMAPER II was able to map both acoustically and optically the spatial and temporal distributions of organisms and physical properties of the water column under sea conditions that have previously rendered surveying impossible.

The challenge of having BIOMAPER II's broad capability now lies in making proper use of the data. Future developments will focus on more integrated methods of analyzing the data and visualizing the results in near real time.

Peter Wiebe

Articulating J-frames used previously, like this one, proved inadequate for handling the BIOMAPER II instrument system.

Geology & Geophysics Department

Three new appointments were made to the G&G resident Scientific Staff in 1999. John Collins, a 1989 graduate of the MIT/WHOI Joint Program in Oceanography, was promoted to Associate Scientist from the Technical Staff where he had worked since 1992. John is a marine seismologist with broad interests ranging from the seismic structure of oceanic lithosphere to shallow water marine sediments. He is an expert in marine seismic instrumentation and was the lead investigator on the successful WHOI proposal to build and operate a new generation of ocean bottom seismic instruments for use by the marine geosciences community in the US (see page 17). Wen-lu Zhu, a 1996 graduate of the State University of New York, Stony Brook, and a WHOI Postdoctoral Fellow, joined the department in February. Wen-lu's research interests include experimental rock mechanics, transport properties of rocks, and the evolution of permeability and pore structures in submarine hydrothermal systems. During the past year she has also been working closely with Associate Scientist Debbie Smith modeling volcanic flow features on the submarine Puna Ridge in Hawaii (see page 15). In September, Rob Sohn joined the department's marine seismology group as an Assistant Scientist from the Scripps Institution of Oceanography, where he received his Ph.D. in 1996. Rob's research interests include seismicity of volcanic and hydrothermal systems, the structure of oceanic crust, and the seismicity of the Arctic Basin. He is currently building a new, combined ocean-bottom-seismometer/autonomous-underwater-vehicle package for use under the Arctic ice.

Tom Kleindinst

Information Systems Associate Tom Bolmer and Summer Student Fellow Patricia Gregg digitize hand-drawn magnetic anomaly contours.

Department promotions for 1999 included Peter Clift and Neal Driscoll to Associate Scientist, and Karl von Reden to Senior Research Specialist.

With the resignation of Dave Aubrey to devote full time to his private company and Alan Chave's transfer to the AOP&E Department, the size of the resident Scientific Staff in G&G stands at 33. We currently also have 22 Technical Staff members, 23 MIT/WHOI Joint Program Ph.D. students, and 14 postdoctoral fellows, scholars, and Investigators working in the department.

In 1999 the Department submitted 182 research proposals, mostly to federal agencies. There were 192 active awards during 1999 for a total of $10.2 million in funding. This research resulted in more than 75 scientific publications in peer-reviewed journals. Department scientists and technical staff members participated in 20 different research cruises in 1999 to far-flung locales such as the Lau Basin near Fiji in the western Pacific, the Mid-Atlantic Ridge south of the Azores, and the South Atlantic off the coast of Brazil.

Senior Scientist Henry J. B. Dick was named a Fellow of the American Geophysical Union in 1999, and Research Specialist Beecher Wooding received a WHOI Senior Technical Staff Award recognizing his outstanding record of accomplishment in instrument design, development, and operation. Paleoceanographer Delia Oppo was named a US Science Advisory Committee Distinguished Lecturer for her work with the Ocean Drilling Program and will be presenting invited lectures at various colleges and universities around the country.

Bill Curry stepped down as Department Chair in October, returning to full-time research in paleoceanography following four years of excellent department leadership. He was succeeded by Bob Detrick, and Senior Scientist Susan Humphris succeeded Bob as the J. Seward Johnson Chair and Educational Coordinator in the G&G Department.

—Robert S. Detrick, *Department Chair*

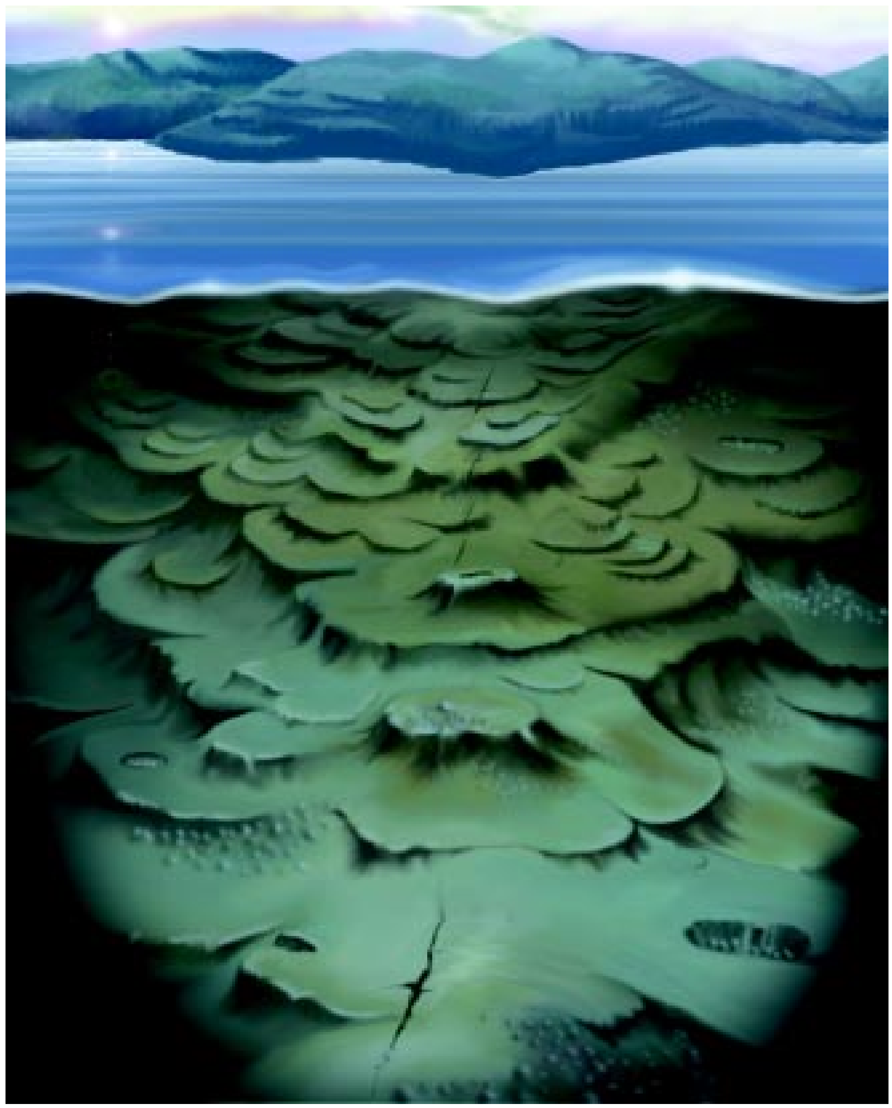
Large Lava Terraces on the Seafloor & their Geological Significance

Wen-Lu Zhu, *Assistant Scientist*
Deborah K. Smith, *Associate Scientist*

Though marine geologists can describe the forms that lava eruptions create on the seafloor, the parameters that control the shapes of basaltic lava flows are not well understood. Why do low-relief flows mantle the topography in some places, while elsewhere the flows form large lava terraces that are several kilometers in diameter and several hundreds of meters high? Is it mostly the result of differences in lava volume, steadiness of flow, pre-existing slope, or flow rate? Answering such questions will help us to judge how confidently we can infer eruption variables from the resulting submarine volcanic morphology. This is especially important because we commonly use the characteristics of lava flows to describe subsurface processes such as mantle melting, creation of magma chambers at crustal levels, and movement of magma within the shallow crust.

Our work is directed towards understanding the formation of flat-topped volcanoes at underwater rift zones using theoretical and experimental modeling. New, detailed images of the seafloor show us that flat-topped volcanoes are commonly constructed at slow- and ultra-slow-spreading mid-ocean ridges, and on the submarine flanks and rift zones of the Hawaiian volcanoes (figure at right). We refer to these flat-topped volcanoes as *terraces* to reflect the fact that they form on slopes and typically have lower relief on their upslope side. Terraces can be large, ranging up to several kilometers in diameter and several hundreds of meters high. One of the interesting features of the terraces is that their top surfaces are almost always horizontal (instead of parallel to the overall topographic slope). They also are remarkably symmetric (near-circular) in plan shape. Also of note is that these features are not common in basaltic flows on land and are not observed at fast-spreading mid-ocean ridges. What does their formation tell us about how submarine rift zones work?

To date, geological applications of theoretical models have focused on describing lava domes that are built at the summits of explosive volcanoes on land. Because the density, viscosity, and thermal diffusivity of seawater, as well as the pressure and temperature conditions at the bottom of the sea, are so different from those of air, it is important that we construct our models using parameters that re-



E. Paul Oberlander

Three-dimensional perspective view of the submarine Puna Ridge rising to connect to the East Rift Zone of Kilauea Volcano on the island of Hawaii. On the East Rift Zone, lava flows mantle the gentle slopes and no large domes or terraces are formed. As the East Rift Zone dips underwater to become the Puna Ridge, the volcanic morphology changes dramatically. The flanks of the Puna Ridge are steeper than the East Rift zone and characterized by tall, voluminous terraces and domes, some with large, collapsed craters on their summits. The authors are constructing a numerical model to explore the origin of these volcanic features. This will help scientists understand controls on the development of this type of volcanic morphology, important because the locations and shapes of submarine volcanoes are commonly used to infer the subsurface structure of oceanic islands and mid-ocean ridges.

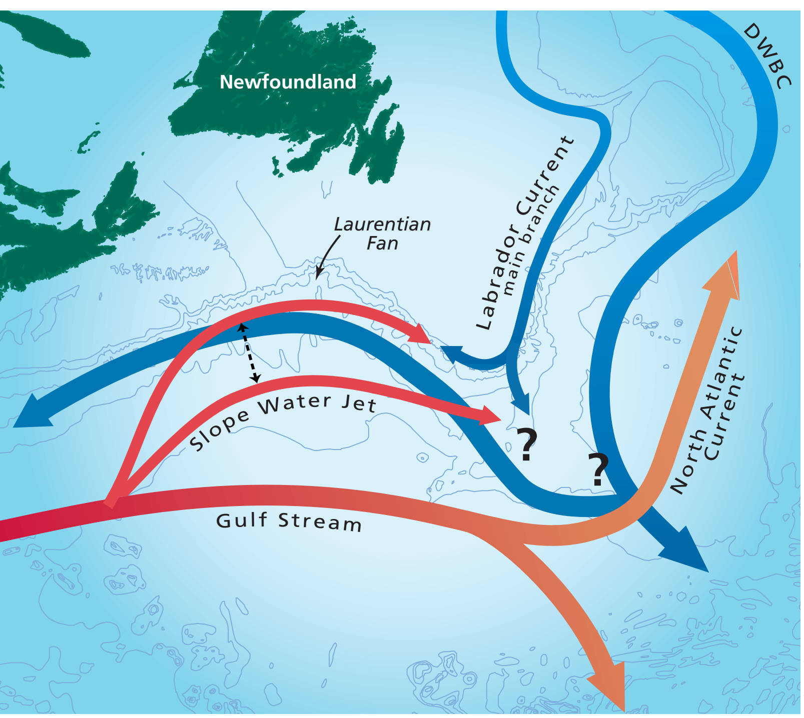
flect the submarine environment. From our preliminary study we conclude that, in general, high lava viscosity, low flow rate, and gentler slopes favor the formation of terraces. We are encouraged by the consistency between our conclusions based on a quantitative fluid mechanics model and what we know from the geology of the features we are trying to model. With these preliminary simulation results, we are now confident that our models will provide a useful tool to quantify and test geological models for the formation of submarine terraces.

We think this is a critical time for our theoretical modeling efforts as we are poised to make several breakthroughs in understanding the controls and characteristics of submarine eruptions. In doing so we will not only gain a better understanding of submarine eruptions, but, more broadly speaking, will gain a better understanding of how the volcanic layer is formed at mid-ocean ridges and how large underwater volcanoes are constructed.

Paleo and Current Oceanography Agree on North Atlantic Warming

Lloyd Keigwin
Senior Scientist

Scarcely a day passes without some media coverage of climate change. Most of the evidence for "global warming" comes from meteorological observations obtained using modern instruments, but a geographically wide array of these data is available for only the past 150 years or so. Interestingly, this time frame includes the end of the climate episode known as the Little Ice Age, a centuries-long cold snap that began before the Industrial Revolution. Thus, scientists want to know how much of the warming since the end of the Little Ice Age is caused by human burning of fossil fuels, and how much represents natural variability.



Flow of warm surface waters (red) and cold deep waters (blue) off Newfoundland. The Slope Water Jet migrates between extreme positions over the Laurentian Fan.

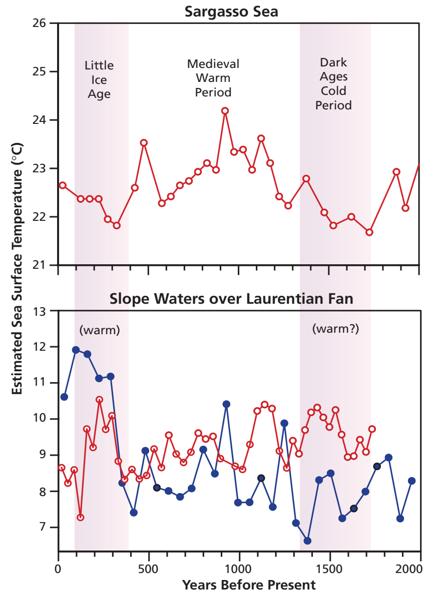
In paleoclimatology, the 1990s could be considered the decade of millennial-scale studies. Early in the decade the first results from European and American drilling efforts in the central Greenland ice cap proved beyond a doubt that climate has been unstable for most of the past 100,000 years. Climate changes in the atmosphere over Greenland are driven in large part by changes in the temperature and currents in the North Atlantic region, and it soon became clear that the best sediment cores from the North Atlantic showed climate oscillations directly comparable to those recorded in the Greenland ice cores. Furthermore, it is now known that the Little Ice Age was the latest in a continuous series of cold events that can be traced across the past 100,000 years.

Now that cold climatic episodes are known to occur every one to two thousand years over vast regions of the globe, the challenge to paleoceanographers is to determine the process of ocean and climate change. With funding from the National Science Foundation, members of the WHOI paleoceanography group are actively engaged in these process studies for regions as far reaching as the southern ocean around Antarctica, off Brazil, in the Pacific, and at many North Atlantic locations.

We found the first open ocean evidence for the Little Ice Age in the Sargasso Sea of the western North Atlantic several years ago. There, northeast of Bermuda, the oxygen isotope ratios in planktonic foraminifera indicated sea surface temperature was lower than today by about one degree during the Little Ice Age. At the time we speculated that surface ocean cooling several hundred years ago may have been similar to modern surface ocean changes associated with the contrast in atmospheric pressure between the Azores and Iceland. This atmospheric phenomenon, known as the North Atlantic Oscillation, operates on an interdecadal time scale and represents a unifying view of sea surface temperature, wintertime mixing, storm tracks, strength of westerly winds, and climate over land in Africa and Europe.

Pursuit of the Little Ice Age led us north from the Sargasso Sea to the slope waters off Nova Scotia and Newfoundland. We reasoned that sediments on the Laurentian Fan would accumulate rapidly enough to resolve the Little Ice Age, and the ocean surface there would potentially record bigger changes than to the south because slope waters are a regime marked by mixing of subpolar waters from the north and subtropical waters from the Gulf Stream. Surprisingly, however, during the Little Ice Age the population of surface ocean dwelling foraminifera contained a lower percentage of polar species than modern sediments of the last century. In other words, at the same time the Sargasso Sea and other North Atlantic regions cooled, the slope waters off Newfoundland warmed. This indicated that the foraminifera settling to the seafloor captured some peculiar dynamic response of the climate system that was much more complicated than a simple regional warming and cooling through time. What process could cause this out-of-phase response?

Discussion of this puzzling ob-



Out-of-phase sea surface temperature relationship between the Sargasso Sea and the Slope Waters during the Little Ice Age.

servation with Bob Pickart of the Physical Oceanography Department revealed that Pickart had just submitted a manuscript summarizing his study of variability in slope waters over the past few decades. His principal conclusion was that the position and intensity of surface and deep flows in the region vary with the North Atlantic Oscillation. In particular, Pickart concluded that a warm surface flow known as the Slopewater Current moves northward when the North Atlantic Oscillation is associated with cooling in the Sargasso Sea. As our cores were located directly under the migrating path of the Slopewater Current, the planktonic fauna would reflect surface water warming to the north of the Gulf Stream when waters to the south cooled.

This fortuitous combination of paleoceanography and physical oceanography strengthens our notion that the North Atlantic Oscillation is a useful model for understanding climate change on long (millennial) times scales. In addition, because Pickart's view of the physical oceanography of the region was based on relatively few repeat hydrographic sections, the long time scale provided by the marine geological data tends to support his interpretation of the modern observations.

A New Generation of Ocean Bottom Seismic Instruments

Robert S. Detrick, *Senior Scientist*
John A. Collins, *Associate Scientist*
Kenneth R. Peal, *Senior Engineer (AOP&E)*
F. Beecher Wooding, *Research Specialist*

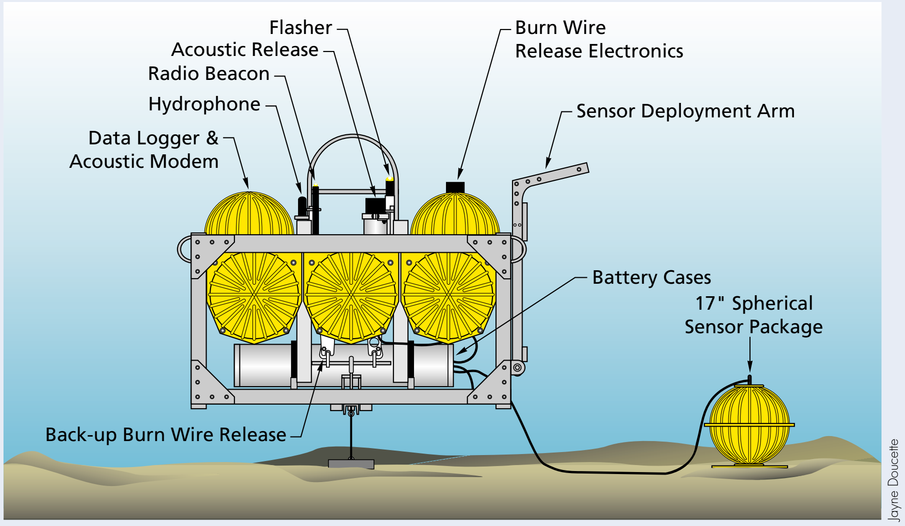
Seismology is an enormously powerful and versatile tool for investigating the structure of the earth's interior and for studying the volcanic and tectonic processes that shape the surface of our planet. Scientists employ seismic techniques to produce three-dimensional images of the structure of oceanic crust and the volcanic systems active at oceanic spreading centers. Along convergent margins (where two tectonic plates collide), like those that rim the Pacific Ocean, seismic monitoring can pinpoint locations and depths for earthquakes and determine the magnitude of earthquake-related strain across the margin. Seismic energy from distant earthquakes recorded on land or on the seafloor allows scientists to produce tomographic images of convection deep within the earth's interior.

Major strides in seismic studies of the continents over the past few decades are not matched by advances in oceanic seismic studies, which are hampered by the difficulty of making measurements on the seafloor. However, major advances in data storage and microprocessor technology are allowing the development of new generations of ocean bottom seismometers (OBSs) and hydrophones (OBHs). This new generation of instruments will be capable of continuous, 24-bit recording of four channels of data (for example, a three-component seismometer and hydrophone) at rates of up to 200 samples per second for several weeks, and at lower rates for up to a year or more. Instruments that can record seismic waves with periods greater than 100 seconds to less than 0.1 seconds will be used in OBSs in the near future, allowing transfer of the whole suite of land-based broadband seismic techniques to the oceans. Reduction in the cost of seafloor seismic instruments now makes it feasible to conduct experiments using 50 to 100 instruments (or more) rather than the 10 to 20 instruments available for most studies in the past.

Recognizing the exciting opportunities in marine seismology today, the National Science Foundation (NSF) in 1999 established a national OBS Instrumentation Pool (OBSIP) to make this new generation of ocean bottom seismic instruments available to the broader geosciences community. Following a national competition, NSF selected WHOI as one of just three institutions in the US to build and operate instruments for OBSIP. (The others are at the Scripps Institution of Oceanography in California and the Lamont-Doherty Earth Observatory in New York.) WHOI has been developing, building, and operating instrumentation for ocean-bottom seismology since 1975, and has a long and successful track record in this area.

These new instruments, described below, which should be available by mid-2001, will usher in a whole new era of marine seismology, allowing investigators at WHOI and elsewhere to study earthquakes, volcanism, and the structure of the crust beneath oceans in ways never before possible.

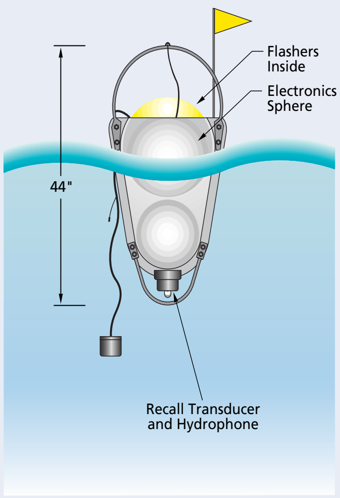
New Ocean Bottom Seismic Instruments



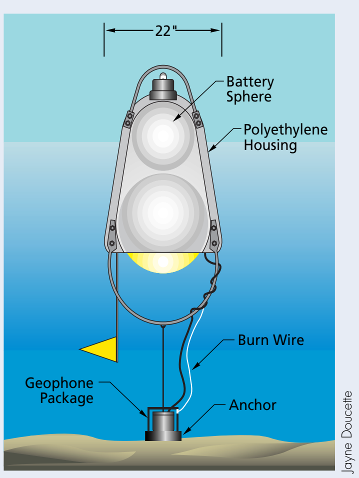
WHOI will contribute two different types of instruments to the national Ocean Bottom Seismic Instrumentation Pool: 50 compact, inexpensive instruments designed for short deployments (typically a few weeks to a month or so) to conduct crustal seismic refraction studies, and 25 long-deployment (up to a year or longer) ocean bottom seismometers (OBSs) for local, regional, and teleseismic earthquakes studies. The short-deployment instrument (see drawing below) will consist of two glass balls with 17-inch and 12-inch diameters. The data logger, clock, release electronics, and recovery aids will be housed in the larger ball; the smaller ball holds a battery pack. The sensors are a hydrophone and a vertical-component 4.5-hertz seismometer. The instrument free-falls through the water column to the seafloor and floats just above its anchor where it records the seismic signals. At the conclusion of the experiment an acoustic signal is sent to the instrument, which releases its anchor and floats to the surface for recovery. Following anchor release, the instrument is designed to invert so that the hydrophone transducer remains submerged even when the instrument is floating on the surface, allowing the recovery team to home in on it acoustically. Once aboard ship, the instruments can be debriefed and their data downloaded without opening the package. The instruments are designed to be deployed and recovered several times on a single research cruise.

The long-deployment instrument (above) is larger and more complex. It carries both a hydrophone sensor, similar to that of its simpler cousin, and a sensitive three-component geophone designed to record ground motion from distant earthquakes. The seismometer is mounted on an arm that rotates and lowers the separate sensor package to the seafloor on receiving an acoustic command from the ship. This OBS will use the same data logger and clock as the other instrument. Batteries stored in two aluminum pressure cases mounted on the frame will allow the OBS to record data continuously for up to 15 months. A low-cost acoustic modem will allow engineers to retrieve data from the package while it is on the bottom and determine if it is properly functioning before leaving the site.

Floating on Surface



Anchored on Bottom



Marine Chemistry & Geochemistry Department

Research in the Department of Marine Chemistry and Geochemistry (MCG) generally involves the quantification of chemical fluxes to and from the oceans. It often focuses on the mechanisms and rates of chemical transport at important ocean boundaries, ranging from the air-sea interface to the interaction of seawater with deep ocean volcanic systems. Other research projects include upper ocean biogeochemical cycles, organic geochemical tranformations, seafloor hydrothermal circulation, photochemistry, atmospheric chemistry, marine aerosols, the sediment-ocean interface, mantle geochemistry, extraterrestrial fluxes to the oceans and atmosphere, anthropogenic contaminants, and remote sensing of the oceans.

The main source of research funding is the National Science Foundation but support also came from the Office of Naval Research, Department of Energy, National Aeronautics and Space Administration, Gas Research Institute, and Seaver Institute. MCG scientists participated in national and international programs such as the World Ocean Circulation Experiment, Earth Observing System, the Ocean Drilling Program, the Ridge Inter-Disciplinary Global Experiments, and the Joint Global Ocean Flux Study, whose national administrative office is housed in the department under the supervision of Ken Buesseler.

In 1999, there were 19 Scientific Staff members, 4 Scientists Emeritus, 19 Technical Staff, 7 graded and 6 administrative support staff, 5 Adjunct Scientists, and 1 Adjunct Oceanographer. In addition there were 15 MIT/WHOI Joint Program Ph.D. students, 13 postdoctoral researchers, and 5 summer fellows. MCG staff taught 6 graduate courses as part of the MIT/WHOI Joint Program.


Tom Kleindinst

The group at work in Kathleen Ruttenberg's biogeochemistry laboratory includes Kathleen, second from right, Joint Program Student Kirsten Laarkamp at right, and, from left, Anastasia Prapas, Nicole Colasacco, and Christie Haupert.

There were a number of important personnel changes in 1999. Kathleen Ruttenburg, who studies nutrient cycling in coastal and freshwater systems, was promoted to Associate Scientist. Two Assistant Scientist appointments brought exciting new research interests to the department: Katrina Edwards is a geomicrobiologist studying microbially induced chemical changes at mineral interfaces, and Wolfgang Bach studies the geochemistry of hydrothermal systems and the ocean crust. The department bid farewell and best wishes to Catherine Goyet who left to take a post at Lawrence Livermore National Laboratory. Dempsey Lott was promoted to Senior Research Specialist, the top rung of the technical staff ladder. Lary Ball was promoted to Research Specialist, Minhan Dai to Research Associate III, and Josh Curtice to Research Associate II.

Senior Scientist Ollie Zafiriou spent three months as an NRC Senior Research Associate at the Environmental Protection Administration laboratory in Athens, Georgia, pursuing his photochemical research. MCG congratulated Senior Scientist Fred Sayles, who received a 1999 Hans Pettersson Medal from the Royal Swedish Academy of Sciences in recognition of his research accomplishments.

—Mark D. Kurz, Department Chair

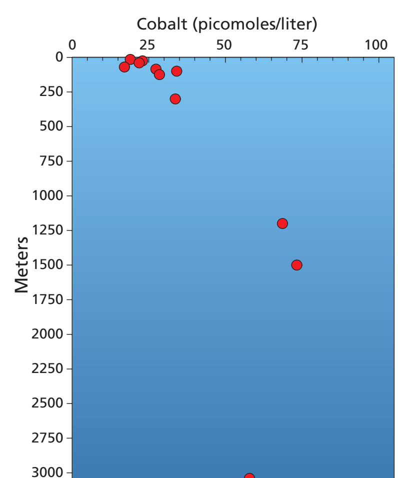
Cobalt: A Key Micronutrient for Marine Phytoplankton

James W. Moffett
Associate Scientist

Seawater contains a large number of trace elements, each exhibiting a unique and complex geochemistry, governed by its chemical reactions in seawater and its interaction with biological processes. The biological processes are particularly important for trace elements that also happen to be essential micronutrients. These include iron, cobalt, copper, zinc, manganese, and nickel, and their importance stems from their utilization within metalloenzymes that catalyze a wide array of biochemical reactions.

Organisms in the open ocean face several problems in acquiring the micronutrients they need. First, micronutrient concentrations are extremely low, in some cases 100- to 1,000-fold lower than in coastal waters, rivers, or lakes. Second, chemical reactions in seawater usually transform these elements into forms that are difficult for organisms to utilize. As a consequence, oceanic phytoplankton are highly adapted to the constraints imposed by their oceanic chemistry.

One of the most important groups of phytoplankton are the cyanobacteria. Often the dominant primary producers in open ocean regions, they are extraordinarily sensitive to their chemical environment, yet, on evolutionary time scales, they are the ultimate survivors. Cyanobacteria are the earliest known organisms, having evolved when there was no oxygen in the atmosphere or oceans. They survived the most dramatic event in the oceans' geochemical history, the shift to an oxygenated regime—thought to be precipitated by their own photosynthetic activities. This event led to drastically reduced levels of essential trace metal micronutrients such as iron and cobalt (which were readily available under anoxic conditions), associated with the oxidation of these elements to nonbiologically available forms. Nevertheless, these organisms not only survived but have thrived owing to physiological adaptations to a new chemical regime that may also have modified the chemistry of the oceans to provide conditions more favorable for growth.



The concentration of cobalt (in picomoles per liter) as a function of depth in the Atlantic Ocean near Bermuda. Low concentrations in surface waters reflect a high biological demand for this scarce micronutrient. The water was collected using stringent clean-sampling techniques, including the specialized sample bottle pictured above.

We are very interested in cobalt, an extremely scarce micronutrient for which cyanobacteria have high requirements relative to other phytoplankton. Joint Program student Mak Saito has been studying the cobalt requirement of *Prochlorococcus*, the most abundant cyanobacterium in the open ocean, and its relationship to cobalt geochemistry. This truly interdisciplinary project has required Saito to develop expertise in trace metal analytical chemistry and microbiology.

Kent Bares

Mak Saito launches a water sampler for work on cobalt's role as a phytoplankton nutrient.

One of his first observations was that most cobalt in seawater is strongly bound by organic matter, probably as metal complexes. Such complexation increases the problem of cobalt availability for cyanobacteria, since organic complexes are generally harder for organisms to take up than dissolved inorganic forms. The ocean's total cobalt concentration is less than one part per trillion; complexation lowers the inorganic form by perhaps 1,000- to 10,000-fold below that! Simple calculations based on the physical transport of this tiny inorganic fraction to the cell surface suggest that the organisms cannot get enough cobalt without a means for accessing the organically complexed cobalt. Working with cultures of *Prochlorococcus,* Saito measured uptake rates of cobalt into the cells under different conditions and found that uptake rates increased the longer the organisms were grown in the same flask of water. He proposed that the organisms had somehow "conditioned" the water, changing the chemistry of cobalt into a form that they can assimilate more readily.

To support his hypothesis, he added seawater that had been exposed to *Prochlorococcus* for a long time to a fresh culture. Cobalt uptake rates increased immediately, indicating that chemical modification of cobalt in the water accounted for the change. We think *Prochlorococcus* produces a compound that binds cobalt, forming a complex that the organism has the specific ability to take up. Though microbiologists have known for decades that bacteria can produce strong iron binding compounds called siderophores, such a mechanism has never been identified for other elements. Currently, we are using the analytical methods Saito developed to study cobalt complexation in the oceans to examine the compounds produced in cultures.

Perhaps the most interesting question is whether the organic compounds that dominate cobalt chemistry in the oceans and the compounds that enhance cobalt uptake in cultures are the same. If so, it raises the possibility that cyanobacteria, and perhaps other bacteria, have modified ocean chemistry on a large scale to create conditions more favorable for growth. This is only a hypothesis, but it is consistent with findings for another key micronutrient, iron. Researchers at the University of California, Santa Cruz, and the University of Western Ontario recently reported that a substantial fraction of iron binding compounds in seawater are siderophores, suggesting that bacterial production of these compounds is influencing the chemistry of iron on a wide scale.

We will ultimately need to learn more about cobalt binding compounds at the molecular level, to test our hypothesis about cyanobacterial sources of these compounds in the oceans, and to learn more about their chemical properties.

How Do High Temperature & Pressure Affect Organic Compounds at Vents?

Jeffrey Seewald
Associate Scientist

Great heat generated by volcanic activity results in convective circulation of seawater through mid-ocean ridge basaltic rocks in a process that has global-scale biogeochemical implications. For example, exchanges of heat and chemicals during hydrothermal circulation cool the oceanic crust, regulate the composition of seawater over geologic time, and result in the formation of metal ore deposits. From a biological perspective, hydrothermal processes support large communities of unusual animals and create the potential for abiotic synthesis of organic compounds from inorganic precursors, causing some scientists to advocate hydrothermal systems as possible sites for the origin of life on Earth.

Despite the important role reduced carbon compounds play in most of these processes, especially those associated with biological activity, we presently know very little about fundamental processes that regulate the generation and stability of organic compounds in high-temperature and high-pressure environments beneath the seafloor. As a result, this area of research is the focus of extensive efforts in the earth science community.

One aspect of ongoing hydrothermal research at WHOI is centered on laboratory experiments designed to elaborate the extent and nature of interactions involving aqueous organic compounds and rock-forming minerals. We have learned that many reactions that proceed readily in the presence of water and minerals do not occur in dry, mineral-free environments. In addition to acting as catalysts, water and minerals react directly with organic compounds and represent a large source of hydrogen, oxygen, and sulfur available for the formation of hydrocarbons as well as oxygen- and sulfur-bearing compounds. These results suggest conditions in subseafloor hydrothermal systems may be appropriate for production of organic compounds from which life originated.

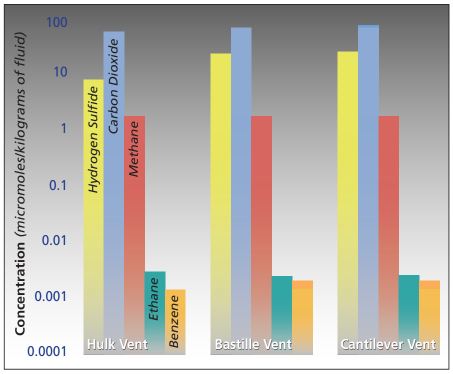

Tom Kleindinst

The remotely operated vehicle Jason's *manipulator holds the specially designed gas-tight hydrothermal fluid sampler.*

Other experiments show that the relative abundance of some aqueous organic compounds may accurately record the reaction temperature and oxidation state of the chemical system, two parameters that strongly regulate metal mobility, rock alteration, and the stability of biomolecules. This is particularly exciting since it suggests that the abundance of organic species in vent fluids provides geochemical information regarding physical and chemical conditions in inaccessible regions of the oceanic crust.

The next step is to test models developed in the laboratory in a natural setting. With funds from a Green Technology Award and the National Science Foundation, I have been working with Ken Doherty, Terry Hammar, and Barrie Walden of the AOP&E Department and Joint Program Student Anna Cruse to build a device for collecting fluids from seafloor hydrothermal vents for organic analyses. This is not a trivial task since operating at seafloor pressures of 200 to 400 atmospheres (3,000 to 6,000 pounds per square inch) in the vicinity of highly corrosive, 400°C fluids presents many engineering challenges. In addition, many organic species are gases requiring that the sampling device be gas-tight to seafloor pressures. The sampler shown in the photo on page 21, constructed of titanium, is easily deployed using the manipulator arms of the submersible *Alvin* or remotely operated vehicles such as *Jason*. A key feature of this sampler is that it allows quantitative characterization of a single fluid in terms of both its organic and inorganic composition, something that has not been possible in the past.

In the fall of 1999 we collected high-temperature fluids (300 to 374°C) venting from basaltic rocks at the Endeavour segment of the Juan de Fuca Ridge. These fluids were extremely gas-rich, containing high concentrations of carbon dioxide, hydrogen, methane, hydrogen sulfide, and low molecular weight hydrocarbons. The bar graph shows concentrations corresponding to as much as 3 liters of gas per liter of fluid at ambient pressure conditions, causing the fluids to fizz upon removal from the pressurized sampler. The high gas content suggests that these fluids represent a vapor phase produced during boiling beneath the seafloor. The presence of substantial hydrocarbons is intriguing, considering they are present at exceedingly low levels in seawater or basalt, and may reflect abiotic synthesis in the crust or derivation from a buried sediment source that is presently not visible.



Jayne Doucette

Gas concentrations in hydrothermal vent fluids from the Endeavour segment of the Juan de Fuca Ridge. Abundant hydrocarbons may reflect abiotic synthesis in the crust or derivation from sediments buried by recent volcanism. Regardless of their origin, these gases represent a source of nutrients and energy to support large and diverse biological communities.

In the summer of 2000 we are scheduled to return to an area of the Juan de Fuca Ridge called Middle Valley where high sedimentation has blanketed the ridge crest with sediments. There is no question that hydrothermal fluids are reacting with both sediments and basalt at this location, and results from these efforts will form the basis for an evaluation of the role of sediment reactions at Endeavour.

Relative to unsedimented systems, the diversity of organic alteration products at Middle Valley is substantially greater due to thermal maturation of sedimentary organic matter and may even lead to the instantaneous (on a geologic time scale) generation of petroleum. Because organic alteration processes responsible for petroleum generation at Middle Valley are in many ways analogous to those occurring in conventional sedimentary basins responsible for economically viable oil deposits, the implications of this research go far beyond the study of ridge-crest hydrothermal systems. Ultimately our efforts will develop and verify new models for the description of organic transformations in subsurface aqueous environments.

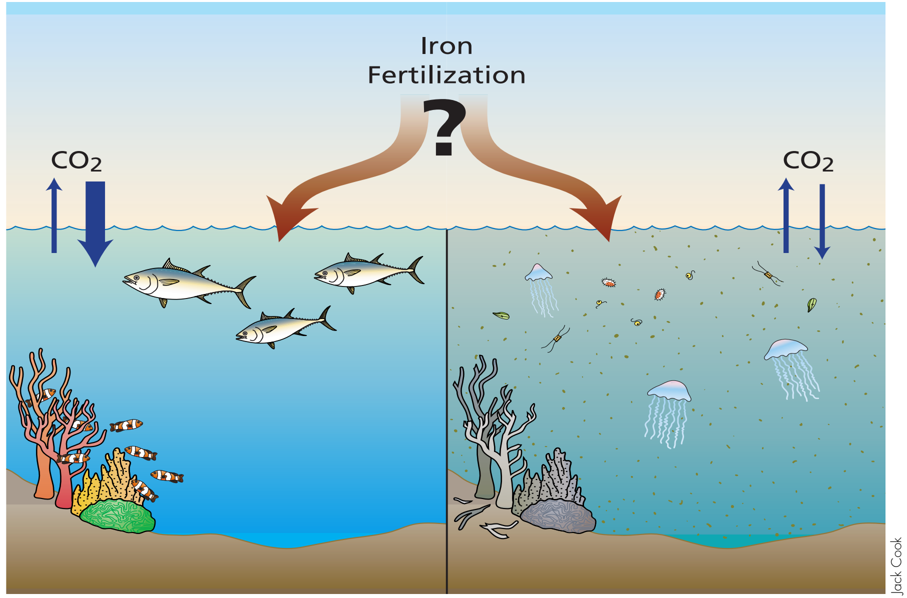
Fertilizing the Ocean with Iron

Ken O. Buesseler
Associate Scientist

Iron fertilization of the ocean is a hot topic not only within the ocean research community but also among ocean entrepreneurs and venture capitalists who see the potential for enhancing fisheries through large-scale ocean manipulations. In the 1980s, the late John Martin (Moss Landing Marine Laboratory) advanced the idea that carbon uptake during plankton photosynthesis in many regions of the world's surface ocean was limited not by light or the major nutrients nitrogen or phosphorus but rather by a lack of the trace metal iron, which is typically added to the open ocean as a component of dust particles. Laboratory experiments and correlations between dust and atmospheric carbon dioxide levels in ancient ice core records suggested that the ocean would respond to natural changes in iron inputs by increasing carbon uptake and hence decreasing atmospheric carbon dioxide, thus altering the greenhouse gas balance and climate of the earth. Martin once dramatically said: "Give me half a tanker full of iron and I'll give you an ice age."

In two 1990s experiments, US investigators led by Ken Coale (Moss Landing Marine Laboratory) purposely "fertilized" a large patch of water near the equatorial Pacific with iron. The results showed a strong biological response and a chemical drawdown of carbon dioxide in the water column.

But what was the fate of this carbon? We know that plant uptake of carbon in the ocean is generally followed by a zooplankton bloom as grazers respond to the increased food supply. These populations then produce a blizzard of marine snow, as fecal pellets and other particles descend through the water column, carrying or "exporting" their carbon load to the deep sea in



Potential long-term outcomes for iron fertilization of the ocean are unknown, and could include newly productive fisheries and reduced atmospheric carbon dioxide (left) or a polluted ocean, unenhanced fisheries, and little effect on atmospheric carbon dioxide (right).

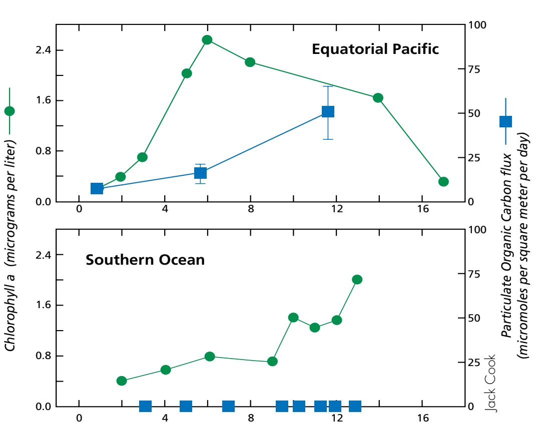
a process known as the "biological pump." Drawing on many years' experience working with thorium in seawater, my laboratory colleagues and I are studying the decrease in surface water thorium following iron fertilization as a proxy for carbon export from the surface to the deep sea. Thorium is a naturally occurring element that by its chemical nature is "sticky," and, due to its natural radioactive properties, relatively easy to measure.

Analysis of a series of seven surface water samples, collected during a 1995 experiment called FeExII, told us that, indeed, as iron was added and plant biomass (measured as chlorophyll) increased, there was a corresponding decrease in total thorium levels. We used the measured thorium decrease to quantify the increase in particulate organic carbon export as particles sank out of the surface layer (upper graph below), noting an interesting delay between the uptake of carbon by the plants and its export as sinking particulate organic carbon. We also noted that the relationship between uptake and export was not 1:1, but rather the iron-stimulated biological community showed very high ratios of export relative to carbon uptake. Thus by the end of the experiment, the efficiency of the biological pump had increased dramatically.

However, results of a similar iron fertilization experiment led by Phil Boyd (University of Otago, New Zealand) during the 1999 summer season in waters south of Australia were very different. The biological response was much slower and less dramatic, and total thorium levels never responded, indicating that the biological pump was not activated (lower graph). We speculate that the difference is due to the colder waters and the resulting slowness of the biological community's response to stimulation. Whether the biological pump turned on after we left the site is a more complicated question, but for now we cannot say that simply adding iron to these waters will result in enhanced removal of atmospheric carbon dioxide to the deep ocean.

The delays in export after an iron-stimulated bloom fits with some of our recent thorium studies in natural systems in the Arabian Sea and in waters around Antarctica. Further work on the effects of iron fertilization in Antarctic waters is scheduled for early 2002. This time we hope to follow the response for 20 to 30 days with a large team of US scientists. In the meantime, the pressure to try something on an industrial scale is mounting and likely to take place with or without scientific input as entrepreneurs gather permits and patent processes for fertilizing the ocean with iron on a large scale.

For example, the territorial waters of the Marshall Islands have been leased to conduct an iron fertilization experiment. The new businesses involved suggest that the iron fertilization process will reduce atmospheric carbon dioxide levels, allowing the Marshall Islands (and other island countries) to profit by trading carbon credits with more industrialized nations. They also point to increased fisheries as a consequence of enhanced iron levels. Prior to these large scale manipulations, more dialogue is needed between these commercial interests, economists, national governments with a marine interest, climate modelers, fisheries biologists, and ocean scientists. While dumping iron may not produce an ice age, it is likely to alter the ocean in unforeseen ways. Whether we end up with productive fisheries and lower carbon dioxide levels, or a polluted ocean with new opportunistic species that do not support enhanced fisheries, is unknown.



Chlorophyll (green) and carbon flux (blue) response to iron fertilization in the Equatorial Pacific and Southern Ocean.

Physical Oceanography Department

The Physical Oceanography Department includes scientists studying the broad scale, general circulation of the oceans on time scales of decades to millennia and ocean mixing scales of centimeters and seconds. They observe the ocean, the atmospheric boundary layer, and interactions of flow with bathymetry, and model fundamental ocean processes.

Lisan Yu joined the department as an Assistant Scientist in 1999, coming to WHOI from the National Aeronautics and Space Administration Goddard Space Flight Center/University of Maryland, where she was an Assistant Research Scientist. Her scientific interests are in the use of remotely sensed data to study interannual oceanic variability in the tropical Pacific and Indian Oceans. Other personnel changes included the departures of two Assistant Scientists, Gidon Eshel and Audrey Rogerson. The resident Physical Oceanography Scientific Staff now numbers 33.

Associate Scientists Glen Gawarkiewicz and Amy Bower both received tenure, and Kurt Polzin was promoted to Associate Scientist. Technical Staff members Heather Hunt, John Salzig, and Dan Torres were promoted to Research Associate II positions.

Four postdoctoral scholars and investigators were in residence in 1999, and a total of 20 physical oceanography graduate students were enrolled in the MIT/WHOI Joint Program. The department also includes 29 Technical Staff members and 18 graded and 11 administrative staff.

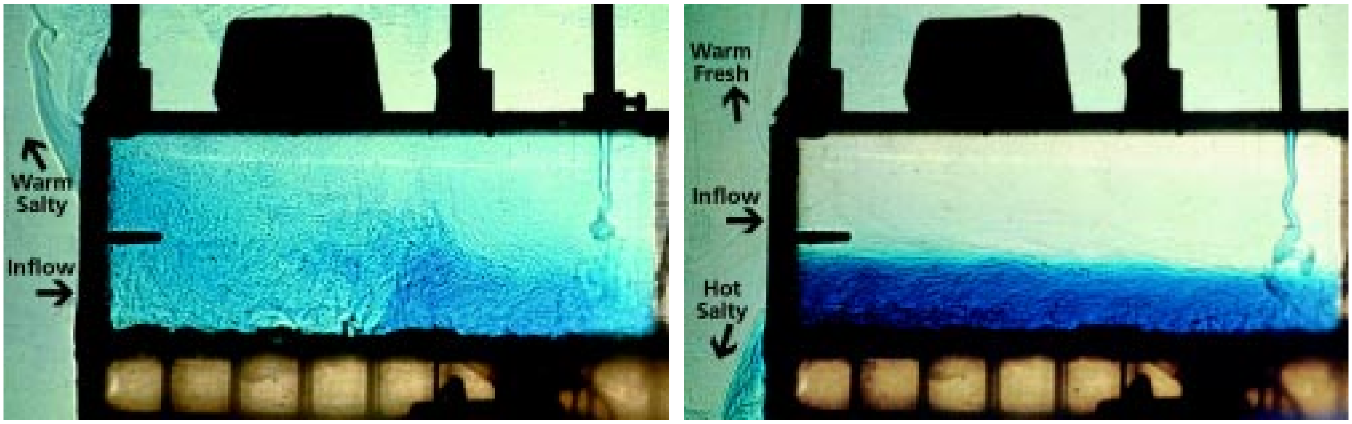
Tom Kleindinst

Research Engineer Paul Fucile assembles electronics for SeaSoar, a tow body that collects physical, chemical, and other data from the upper water column.

The research of two department scientists was honored and enhanced by the US Navy when Senior Scientist Bob Weller received the Secretary of the Navy/Chief of Naval Operations Oceanographic Research Chair and Associate Scientist Steve Anderson was named an Office of Naval Research/Institution Scholar.

During 1999, visiting scientific investigators came to the Physical Oceanography Department from the University of Las Palmas, Canary Islands; Institut Française de Recherche pour l'Exploitation de la Mer, Brest, France; Instituto de Astronomia y Meteorología, Mexico; Chinese Academy of Sciences, Beijing; University of Alberta, Edmonton, Canada; and Commonwealth Science and Industrial Research Organization, Hobart, Tasmania.

—Terrence M. Joyce, Department Chair



John Whitehead

Color shadowgraphs show two modes of flow in laboratory experiments that employ submerged Plexiglas boxes heated from below. Blue-dyed salt water flows into the boxes at top right, and there are slots on the left that allow water in the boxes to exchange with the surrounding water bath. The two experiments exhibit the two-layer "T-mode" at left and the three-layer "S-mode" at right.

Laboratory and Theoretical Studies Elucidate Doubly Driven Flows

John A. Whitehead
Senior Scientist

In the ocean a number of boundary conditions influence water motion. These include wind stress, heat transfer from the earth, heat transfer to and from the atmosphere, precipitation, and evaporation. Internal factors such as solar heating and tides also influence the flows. Each boundary condition requires detailed study to determine its relative importance in generating flows compared to all the others. As a result, numerical modelers and theoretical oceanographers usually limit their studies to simplified models with flows driven by the one or two boundary conditions that they consider the most powerful. However, in some cases a combination of boundary conditions produces features that are absent if the combined actions are simply summed.

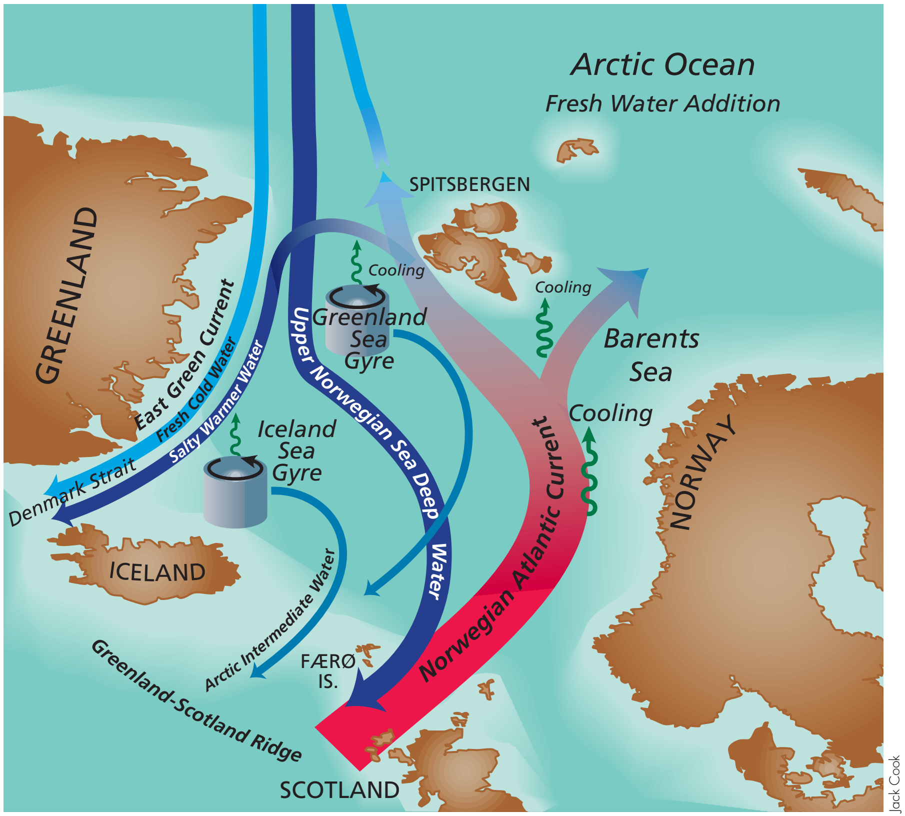
We have used laboratory and theoretical studies to investigate some of the interesting, yet perplexing, aspects of flows driven by combined boundary conditions. Flows can, for example, exhibit multi-equilibrium states, that is, exactly the same set of boundary conditions may produce more than one steady, stable physical flow pattern. In other cases, the flows cycle back and forth through two states, producing natural oscillations. Understanding the origin of such natural cycles is vital to understanding ocean fluctuations as well as those in weather and climate. To date, we have constructed five devices that help to reveal these features.

In one device, a transparent Plexiglas box with a vertical slot in one side is immersed in a large tank of fresh, constant temperature water. Two boundary conditions force fluid motion in the box. The first involves pumping salt water downward at a carefully controlled, fixed rate through a tube that extends into the top of the box. The second boundary condition involves maintaining a fixed temperature in the floor of the box (a copper plate in contact with a hot thermostatically controlled fluid bath). The two boundary conditions force motions with opposing tendencies: The upper mixture becomes denser from inflowing salt water and tends to sink, while the lower, heated mixture becomes lighter and tends to float upwards. The slot in the side of the tank produces density driven exchange currents. These lateral currents allow the heated mixture (or mixtures) to exchange with the room temperature fresh water outside the box and thus contribute to determining the salinity and temperature of the mixture inside the box.

The injected salt water was dyed blue, allowing us to observe the salinity of the water (photos above). A wide range of parameters produced two distinct flow patterns. The first or "T-mode" is characterized by an outflow of warm, diluted, salty water through roughly the top half of the slot, and an inflow of fresh water in the bottom. The second or "S-mode" pattern has three layers. Warm, diluted, slightly salty water flows out at the bottom, fresh water flows into the box at mid-depth, and warm, fresh water flows out of the top.

The different patterns of flow for the two modes are a result of limited mixing. For example, if the water inside the box were strongly stirred, the "T-mode" would be the same, but the "S-mode" would be completely mixed, eliminating the layering. Mixing rate is governed in this experiment by the elevation of the tube that injects the salt water. If the tube is close to the bottom of the box, there is limited mixing of salt water, and vice-versa for higher tube elevations. In some cases either mode is found, depending on history. In others, T-mode and S-mode oscillate irregularly back and forth.

The box represents a simple model of an ocean basin exposed to evaporation and heating. Flow through the slot models exchange of water with another region where the water is colder and fresher. Due to certain symmetries, this box also



Various currents move water north into the Nordic seas and south over the Greenland-Scotland Ridge complex. The Norwegian Atlantic Current (red) carries warm, salty water to the north where it is cooled, mixed, and diluted by fresh water from melting ice and continental runoff. The two flows shown in dark blue transport cold, salty water south, and the lighter blue East Greenland Current moves cold, freshened water south. The split of the warmer, salty inflow into two outflows, one cold and salty and the other cold and fresh, is also expressed as the "S-mode" in laboratory experiments.

provides a simple inverted model of an ocean basin exposed to fresh water runoff and cooled from above, such as in the Arctic Ocean and Nordic seas. In that case, rather than fresh water, the outer tank corresponds to the warmer, saltier water of the North Atlantic Ocean. However, the currents that exchange the waters of the North Atlantic and the Nordic seas are three-layered, as sketched in the map at left. Thus the exchange is closer to our S-mode. Moreover, a simple model of the Arctic Ocean has been generated, adapting for cooling at the surface and freshwater runoff from continents. In this model, the Arctic halocline (a layer of low-salinity water that extends to about 100 meters) is equivalent to our lower layer of salty water in the S-mode (photo on right, page 25). This new finding is difficult to produce in numerical models using fixed mixing rates. The fact that such simple structures are still being found and debated illustrates the large challenges faced by those who hope to understand ocean climate.

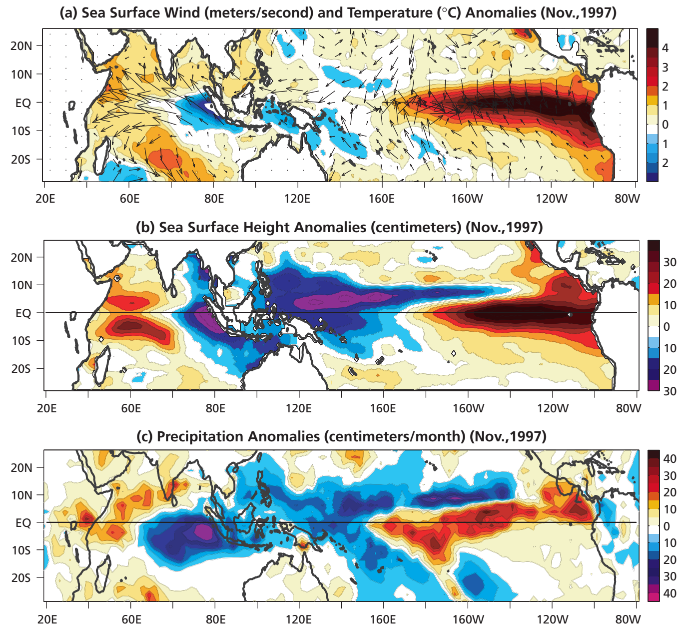
Satellite Observations Reveal Indian Ocean Climate Extremes

Lisan Yu
Assistant Scientist

In 1997 and 1998, during one of the tropical Pacific's strongest El Niños on record, a sequence of disastrous events occurred in the countries surrounding the Indian Ocean. Rainfall in Kenya, Somalia, and Ethiopia was 40 inches above normal, while in the east, large-scale forest fires raged in drought-stricken Indonesia. At the same time, the sea-surface temperatures in the Indian Ocean were rising. By the spring of 1998, record-high surface temperatures were reported over almost the entire basin (lower figure at left, page 27). The warming extreme took a heavy toll in the region where 60 percent of the world's coral reefs are located. Unprecedented bleaching was reported from Sri Lanka to Kenya and the Seychelles, where reefs whitened from the surface down to 50 meters, with mortality as high as 90 percent.

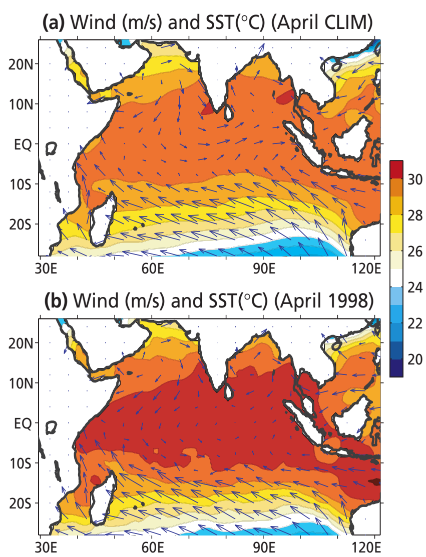
Indian Ocean circulation features a strong seasonal cycle due to the influence of the annually reversing monsoon wind. The climate extremes in the Indian Ocean in 1997–98 were a major perturbation to the normal state. Understanding such anomalies depends upon understanding air-sea interactions and their influence on atmospheric and oceanic mean circulation. Meteorological parameters, such as clouds, precipitation, sea-level pressure, and surface wind, as well as oceanic parameters, such as sea-surface temperature (SST) and height (SSH), salinity, and current, all must be considered.

With advances in space technology, many essential meteorological and oceanic parameters can now be directly derived from satellite remote sensing. Satellite observations for 1997 and 1998 have helped to reveal a "dipole mode" in the equatorial Indian Ocean—simultaneous and related negative SST anomalies off the coast of Sumatra and positive anomalies in the western equatorial region. The mechanism governing the dipole mode is a coupled interaction between atmo-



Anomalous atmosphere-ocean conditions in the Indo-Pacific Oceans in November 1997. The observations are derived from satellite remote sensing. (a) sea surface wind and temperature, (b) sea surface height, and (c) precipitation.

sphere and ocean, akin to that of El Niño in the tropical Pacific. During El Niño, anomalously high pressure develops in the Australasian region, which reduces regional organized deep convections and reverses equatorial zonal circulation in both the Indian and Pacific Oceans (top figure at right). In 1997, the anomalously westward winds in the equatorial Indian Ocean produced considerable oceanic upwelling off the coast of Sumatra and downwelling in the west (middle figure at right). The upwelling brought cold water to the surface and lowered SST, while downwelling had the opposite effect on SST. This produced a reversed SST east-west gradient along the equator, which further supported and prolonged the westward wind anomalies. In response to the SST changes, atmospheric convection centers and precipitation patterns were shifted across the equatorial Indian Ocean, resulting in disastrous flooding in the eastern African countries and severe drought in Indonesia and neighboring regions (lower figure at right). Sea surface winds were light in the first half of 1998. This reduced the amount of heat released by the ocean and weakened oceanic mixing, resulting in a warmer surface layer. Upper ocean temperature profiles acquired along commercial ship tracks confirmed that the warming was largely confined to the upper 50 meters, within which the widespread coral bleaching occurred.



Monthly mean sea-surface temperatures and wind fields in April during (a) a normal year and (b) 1998.

The Indian Ocean dipole mode and the basin-scale warming in 1997–98 displayed a close relationship to El Niño in the Pacific. However, such a striking connection does not always exist. Historic records indicate that, in some years, the dipole mode occurred without El Niño. Even more interestingly, the dipole mode seems also to be independent of the basin-scale warming event. The complexity of Indian Ocean interannual variability and its perplexing relationship with El Niño/Southern Oscillation pose a significant challenge for climate prediction in the Indo-Pacific sector and open a new, exciting area of research.

This research is supported by the National Aeronautics and Space Administration.

ULTRAMOOR: A Low-Cost, Long-Lived Subsurface Mooring Platform

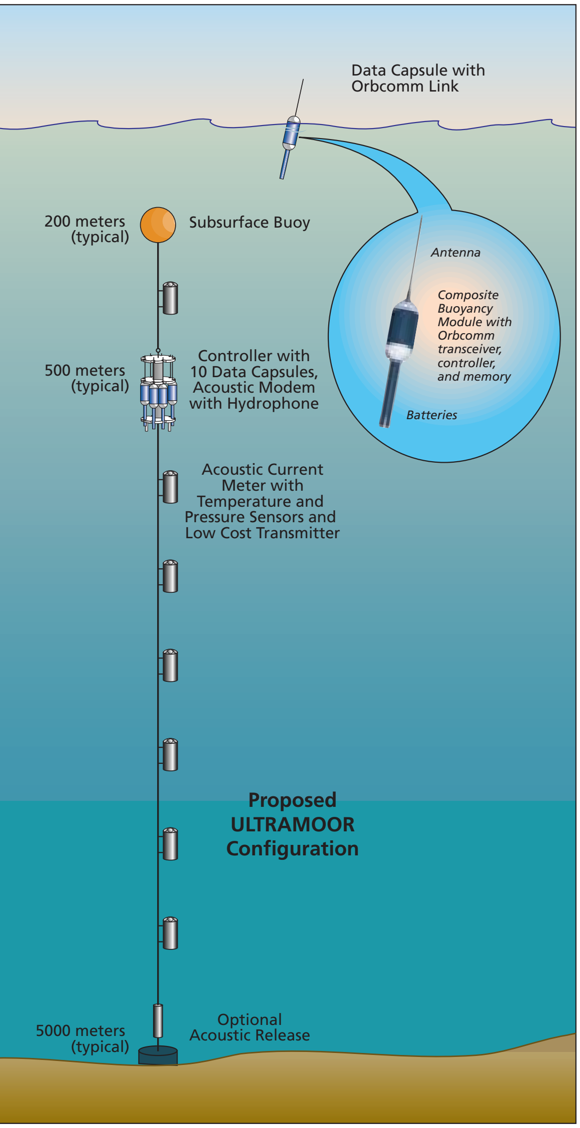
Nelson Hogg, *Senior Scientist*
Carl Wunsch, *Guest Investigator*
Dan Frye, *Senior Research Specialist (AOP&E)*

Eulerian velocity field measurements (those made at certain places) underlie almost all our theoretical structure for understanding the ocean. Despite this history, as oceanographers focus on basin- and global-scale studies, use of deep sea moorings has diminished—apparently because they are expensive to deploy, large numbers are required to depict a global-scale ocean, and there is a long wait (perhaps years) for access to data when the instruments are recovered. However, we believe that the oceanographic and climate communities will continue to need extensive Eulerian measurements and are therefore developing a new subsurface mooring concept.

The ULTRAMOOR (ULTRA-long-life MOORing system):

1) is less expensive and requires fewer and less skilled people to prepare and deploy than present systems,

2) is sufficiently reliable and con-



Jack Cook

servative of power that durations of five years or more will be possible (we hope for 10 years),
3) telemeters its data ashore, and
4) is mechanically simplified to the point that it can be deployed from a vessel of opportunity, not necessarily oceanographic, with a minimum of assistance. Ultimately, we believe that an expendable mooring will be achievable.

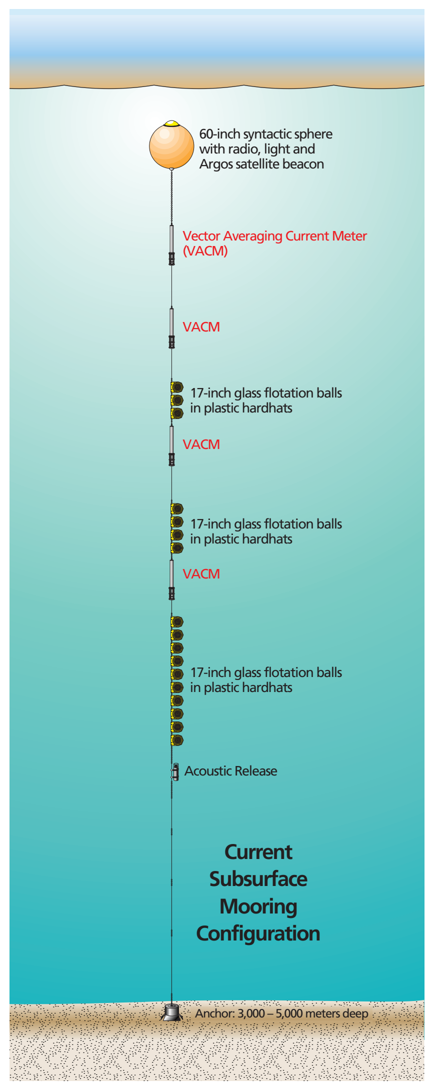
This project, supported by the Oceanographic Technology program of the National Science Foundation and matching funds from the Institution, has been underway since October 1998.

The present subsurface mooring (see drawing at right) has changed little since the early 1970s when it was developed by the Institution's Buoy Group. The main advance has been to extend its lifetime to about two years, but the technology has remained fairly static: Its workhorse Vector Averaging Current Meter is a behemoth by today's standards, weighing in at over 50 kilograms, though it has proven to be a reliable data collector in spite of its dependence on mechanical devices such as rotors, vanes, and jeweled compasses. The mooring itself is constructed from rugged materials intended to resist corrosion and fish bites but requiring heavy-duty winches and skilled technical support for preparation and deployment. With increasing interest in global change climate issues, servicing costs over extended periods and the greater likelihood of mechanical failure have motivated us to reconsider all aspects of the system.

Our vision for the new subsurface mooring (left) is one constructed from noncorrosive, lightweight, synthetic materials that both support scientific instruments and send their data acoustically to a receiving module typically positioned well below the sea surface (500 meters, say) to minimize biological fouling. This receiving module, the Data Collection Magazine (DCM), then transmits its data by electromagnetic induction to buoyant capsules arranged around its periphery. These capsules are programmed to release sequentially (one every 6 months for 5 years, for example), rise to the surface, and transmit data ashore via satellite. Development of the DCM and its data capsules has received the most attention over the past year, including testing in the "well" of the WHOI pier. We expect the DCM to be versatile and useful beyond ULTRAMOOR in other applications requiring periodic remote transmission of underwater data. A prototype of the full system will be moored off Bermuda in July 2000 for a six-month test in which six data capsules will be released on an accelerated schedule. If all goes well, a two-year test will follow.

At present, we are evaluating current meters for ULTRAMOOR; fortunately, the industry is actively developing small, inexpensive instruments based on one of two acoustic techniques: the difference in time it takes for sound to travel in opposite directions (this difference being proportional to the fluid speed in that direction) or the Doppler shift that results when sound is reflected back to a transducer off particles carried in the water. We are also developing new and simplified procedures for installing instruments on a continuous mooring line and a Web-based system for acquiring and distributing data.

We envision a day, not too far in the future, when a host of ULTRAMOORs located around the world will provide oceanographers with valuable and timely information on the state of the ocean.



Jayne Doucette

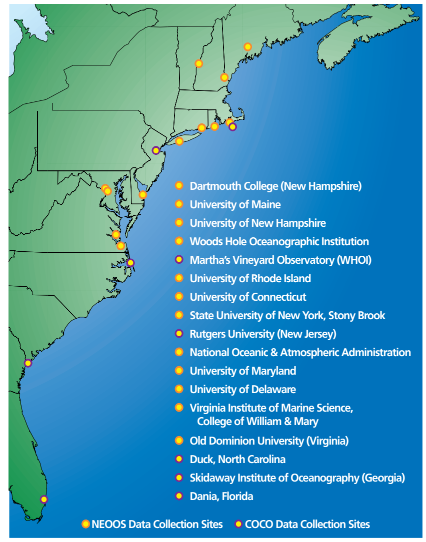
Cooperative Institute for Climate and Ocean Research

In 1998, the Woods Hole Oceanographic Institution and the National Oceanic and Atmospheric Administration (NOAA) established a Cooperative Institute for Climate and Ocean Research (CICOR). This institute ties WHOI to the 10 NOAA research laboratories and to 10 other NOAA Joint Institutes throughout the United States that fall under the agency's Ocean Atmosphere Research Division. Joint research is underway with the closest NOAA research lab, the Northeast Fisheries Science Center in Woods Hole, with the Atlantic Oceanographic and Meteorological Laboratory in Miami, and with the Pacific Marine Environmental Laboratory in Seattle. In addition, climate-related studies by WHOI scientists have been funded by NOAA's Office of Global Programs.

CICOR research activities are organized around three themes: the coastal ocean and nearshore processes, the ocean's participation in climate and climate variability, and marine ecosystem processes analysis. Investigations undertaken in 1999 include Atlantic and Pacific climate studies, improvement of marine surface meteorological measurements and instrumentation, and work on the coupling of the atmosphere and ocean on seasonal time scales in the eastern tropical Pacific.

In partnership with researchers at the Institute for Marine and Coastal Science of Rutgers University and the University of Maryland, CICOR helped to initiate the NorthEast Ocean Observing System (NEOOS), a New England/North Atlantic regional prototype for a network of Global Ocean Observing System (GOOS) centers. CICOR scientists are developing a real-time data dissemination system drawing from data sources along the East Coast from Maine to Florida, both on the coast and at sea. NEOOS will coordinate regional activities, establish mechanisms for data exchange, encourage the development of coordinated, cooperative activities, identify and coordinate user communities, and interpret GOOS user needs.

CICOR was also involved in the effort to establish a global array of profiling floats, known as Argo (Array for Real-time Geostrophic Oceanography). Argo's goal is to provide unprecedented global coverage of upper ocean temperature and salinity structure in real time. This would allow scientists to track the evolving physical state of the ocean and reveal the physical processes that balance the large-scale heat and freshwater budgets of the ocean. It will also provide a crucial dataset for initialization and data assimilation in seasonal to decadal climate forecast models. The Argo network is a major international initiative in oceanography.



Jim Canavan

CICOR is part of the Northeast Ocean Observing System (NEOOS), a regional prototype for a network of Global Ocean Observing System centers. COCO stands for "Coalition of Coastal Observatories," a subset of NEOOS.

CICOR's first Postdoctoral Scholar, Fiamma Straneo, arrived in November from the University of Washington where she completed her Ph.D. with a thesis titled *Dynamics of Rotating Convection Including the Effects of a Horizontal Stratification and Wind*. Working with Associate Scientist Bob Pickart, she is investigating the observed interannual variability in the formation and export of Labrador Sea water.

WHOI Scientists involved with the three CICOR themes are encouraged to visit NOAA laboratories and to invite NOAA and other scientists to visit WHOI in order to build toward future joint research in CICOR's areas of interest. The first CICOR visitor, Fei-Fei Jin of the University of Hawaii, arrived in December 1999 to collaborate with WHOI physical oceanographers in the subject areas of the equatorial thermocline, the equatorial undercurrent, and cross-equatorial flow.

CICOR hosts a Web page and a newsletter. The Web page

Nancy Brink

National Oceanic and Atmospheric Administration Joint Institutes Program staff members Marilyn Moll, left, and Linda McLaughlin enjoyed the CICOR open house with Jim Luyten, center, Bob Gagosian, and Maurice Tavares.

(www.whoi.edu/science/cicor) links to current research projects and supports NEOOS. The first issue of the CICOR Newsletter, *The Bridge*, was distributed in November to the other joint institutes, affiliated NOAA research labs, and CICOR participants.

As an outreach project, CICOR, along with Sea Grant, supported the Blue Lobster Ocean Sciences Bowl held in February at the New England Aquarium. This competition among Massachusetts high schools helps promote the marine sciences and feeds into the national Ocean Sciences Bowl.

—Robert A. Weller, CICOR Director

Marine Policy Center

The Marine Policy Center (MPC) conducts social scientific research to advance the conservation and management of marine and coastal resources. The work of MPC researchers integrates economics, policy analysis, and law with WHOI's basic strengths in the ocean sciences and engineering.

Many MPC research projects reflect the increasing demand for approaches to environmental policy that are compatible with the goals of economic efficiency and growth. Examples include a study to identify cost-effective strategies for remediating PCB contamination in the Hudson River, development of economic models for assessing the socioeconomic impacts of environmental regulation or ecosystem change in particular coastal regions and localities, and a project that will provide the first comprehensive analysis of the US ocean economy in 30 years.

In 1999, MPC researchers developed a model for estimating the cost-effectiveness of various combinations of two general approaches to removing PCBs from the lower Hudson River: dredging PCB "hot spots" north of the Federal Dam at Troy, New York, and improving the rate of PCB removal from wastewater at treatment facilities that discharge into the Hudson further downstream. The model is designed to be integrated with a physical model of the region's multiple PCB sources, flows, and fates. It involves estimation of the costs of various remediation plans, where the objective is to minimize the total cost of achieving a specified maximum level of PCB concentration in sediments, water, or fish after a given number of years.

Also in 1999, MPC launched two projects in an important new area of research concentration that involves the use of "input-output" models to estimate the economic impacts of environmental regulations or ecosystem disruptions. Input-output models characterize the nature of interactions among sectors of the economy, and thus capture the market value of goods and services produced in different economic sectors that are linked to a marine sector, such as commercial fishing.

J. Burkholder, North Carolina State University

Skin lesions in these menhaden from the Neuse River in North Carolina are thought to be caused by a bloom of the harmful algae Pfiesteria spp.

In one such project, MPC researchers are collaborating with investigators from the National Oceanic and Atmospheric Administration's Northeast Fisheries Science Center in Woods Hole to estimate the social economic impact of fisheries regulation in New England. Using primary data collected as part of the project, the project team has modified and extended the standard IMPLAN modeling software and dataset to produce the MARFIN (Marine Fisheries Initiative) input-output model, which captures a number of fishing-related sectors in 11 coastal subregions and one noncoastal subregion of New England. For each of the marine subregions, MARFIN includes seafood harvesters (subdivided according to 17 types of fishing gear), dealers, processors, and other marine-related sectors such as water transportation, shipbuilding and repair, and warehousing. The MARFIN model will be used to assess the impact of various management alternatives, such as fisheries closures or restrictions on the use of certain gear types, on the New England economy and the economies of specific subregions.

Another MPC project uses the input-output methodology to estimate local, regional, and national economic impacts of outbreaks of harmful algal blooms (HABs). Over the past several decades, HABs have involved an increasing number of species and have occurred in a growing number of locations in US coastal waters and around the world. They can result in a range of adverse public health and environmental effects, with significant economic consequences.

Nonetheless, very little work has been done to account for the economic impacts of HABs in the United States. Only one study to date, conducted by MPC researchers and collaborators from the WHOI Biology Department and the Massachusetts Maritime Academy, has attempted to integrate estimates from disparate sources of the economic impacts of individual HAB events. Completed in 1998, the study conservatively estimated that HAB outbreaks occurring from 1987 through 1992 produced direct economic impacts in the range of only $50 million annually.

Using the input-output methodology, MPC researchers are now extending the analysis to include HAB outbreaks through 1998 and to estimate impacts across economic sectors in various regions and localities.

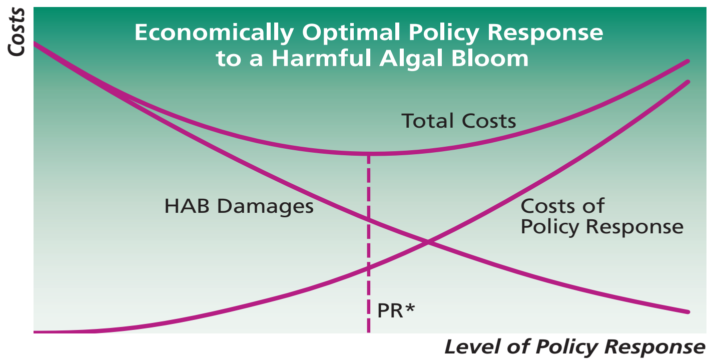
Upcoming MPC studies call for coupling a regional input-ouput model of a coastal economy with a model of a marine food web to enhance understanding of the relationship between economic conditions and alternative ecosystem states. Merging the two types of models will permit estimation of both the economic impacts of changes in ecosystem structure and the effects on the ecosystem of expanding demands on coastal resources.

Policymakers increasingly express interest in this type of study approach, reflecting a growing recognition that ecosystem conservation depends upon political decisions and that political decisions, in turn, are influenced by their potential economic consequences.

MPC researchers also recently participated in the planning phase of a multi-year project to analyze the size and composition of the US ocean economy. Most previous efforts of this type have focused more narrowly on particular geographic areas or ocean economic activities and have produced estimates of the value of ocean-related gross domestic product (GDP) that range widely from 2.6 percent to 35 percent of total GDP.

The project, a collaboration with colleagues at the University of Southern California and the University of Southern Maine, is designed as a meta-study that will utilize, and assess the reliability and relevance of, hundreds of data sources. In addition to data from the core National Income and Product accounts used to measure GDP, the MPC study will incorporate data from regional accounts for coastal states, counties, and other jurisdictional units, data on the "capital value" of the oceans (the ability of ocean resources like fish and minerals to produce income), and data on ocean-generated values derived from outside market transactions, such as the value of recreational and aesthetic amenities or the assimilative capacity of marine waters. The study results will be an important element of the US statistical information infrastructure and will aid in decisions that require balancing growth and conservation in coastal areas.

—Andrew R. Solow, Center Director



MPC researchers are studying ways to estimate both the economic damages of harmful algal blooms (HABs) and the costs of alternative public policy responses. A rational response is to minimize the sum of damages and response costs (PR).*

Rinehart Coastal Research Center

The Rinehart Coastal Research Center (RCRC) bridges department boundaries to encourage and initiate coastal research activities within the WHOI community. With the endowment established by the generous gift from Gratia Houghton Montgomery, RCRC provides approximately $200,000 per year to support coastal research efforts by WHOI scientists. In addition, the Center houses first-rate laboratory facilities and a fleet of small vessels for access to coastal waters. The Center publishes a full-color newsletter twice per year to communicate WHOI's coastal research activities to the scientific community, WHOI's supporters, and the interested public. The Center also sponsors special seminars and workshops and presents the Buck Ketchum Award to distinguished coastal scientists.

Joint Program student Patrick Miller and his research team record sounds of a killer whale using the towed beamforming array off Vancouver Island.

The Buck Ketchum Award is named for oceanographer Bostwick H. "Buck" Ketchum, a scientist at WHOI for more than 40 years who had a fervent commitment to interdisciplinary research in the coastal environment. The 1999 recipient of the Buck Ketchum Award is Willard "Billy" Moore from the University of South Carolina. Moore's outstanding contributions to our understanding of the coastal ocean through the study of radionuclides and his use of radium isotopes to study the fate of terrestrial runoff in the ocean have had broad impact across all of the oceanographic disciplines. His recent results suggesting a major or even dominant role of groundwater in the freshwater input to the coastal ocean is one of the most exciting new developments in coastal research. In the Buck Ketchum tradition of interdisciplinary cooperation, Moore's June seminars attracted scientists from all disciplines, and his informal discussions helped kindle excitement among WHOI scientists for the study of groundwater in the coastal ocean.


Tom Kleindinst

Center Director Rocky Geyer, right, and WHOI Director Bob Gagosian, left, (in the white shirts) chat with visitors during a Rinehart Coastal Research Center open house in June.

A recent RCRC research project involved testing and demonstrating a new towed hydrophone array system developed to study the sounds of marine mammals in coastal waters. Because humans cannot localize underwater sounds, it is notoriously difficult for researchers to locate or identify a signaling marine mammal. This difficulty complicates efforts to measure basic features of marine mammal sounds such as signal source levels or directionality and makes a detailed analysis of sound use by individual animals impossible in most cases. Senior Scientist Peter Tyack and Joint Program student Patrick Miller developed a towed beamforming array to measure the angle-of-arrival of underwater sounds, similar to what human ears do for in-air sounds. By towing one or two of these arrays near wild killer whales in the waters off Vancouver Island, Tyack and Miller proved it possible to measure the source levels of sounds and identify signaling individuals in many cases. Miller completed a final cruise with RCRC support in the summer of 1999 to collect data for his Ph.D. dissertation that explores the design and use of sounds produced by free-ranging killer whales. This new acoustic sampling system will be an important component in future efforts by WHOI researchers to study the acoustic behavior of free-ranging marine mammals and to assess potential negative impacts of underwater noise.

RCRC flume facilities have seen considerable activity in the last year. Cheryl Ann Butman and Richard Zimmer (University of California, Los Angeles) are conducting an innovative set of experiments on the influence of flow on the behavior and settlement of larvae. Knowledge of the factors determining when and where larvae settle on the bottom is critical for understanding the life cycle of a species and ultimately for predicting adult population sizes and distributions. Experiments are being conducted in the 17-meter flume and a small annular flume at the Coastal Research Laboratory. Combining several new technologies for monitoring the movements of individuals within a flow field, these experiments address the relative importance of passive transport versus larval behavior in response to chemical or hydrodynamic cues in determining suspended and benthic larval distributions. Zimmer is using laser light sheets, highly sensitive video cameras, and a custom-built Computer Assisted Video Motion Analysis System to document the motion of larvae within these flumes. This advanced instrumentation is helping Butman and Zimmer unravel the complex interplay of behavior and flow that determine the patterns of larval settlement. It could lead to improved theory on the mechanisms that control larval supply to established populations and new habitats.

—Wayne R. Geyer, Center Director

WHOI Sea Grant Program

The WHOI Sea Grant Program supports research, education, and advisory projects to promote the wise use and understanding of ocean and coastal resources for the public benefit. It is part of the National Sea Grant College Program of the National Oceanic and Atmospheric Administration (NOAA), a network of 29 individual programs located in each of the coastal and Great Lakes states. The goal of the program is to foster cooperation among government, academia, and industry. WHOI Sea Grant-supported projects provide linkages between basic and applied aspects of research and promote communication among the scientific community and groups that utilize information on the marine environment and its resources.

During 1999 the WHOI Sea Grant Program supported 19 current research projects and 10 new initiative awards. The 1999–2000 research projects encompass three theme areas: Estuarine and Coastal Processes, Fisheries and Aquaculture, and Environmental Technologies. Many of the projects address local and regional needs; some have national or even global implications. Investigators from the Woods Hole scientific community, universities throughout Massachusetts, and scientists from industry and other states all participate in WHOI Sea Grant's competitive funding process. Examples of currently funded projects include:

• Dynamics of the Toxic Dinoflagellate, *Alexandrium*, in the Gulf of Maine: Source Populations and Downstream Impacts.
• Impacts of Accelerated Sea Level Rise in Storm Induced Sedimentation on Southern New England Coastal Wetlands.
• Laboratory Based Transmission of the QPX Parasite in Cultured Hard Clams and Studies on the Progression of the Disease.
• Understanding the Potential of Offshore Mariculture: A Bioeconomic Approach.
• Reproductive Strategies and Their Contribution to Genetic Diversity and Life Cycle Flexibility in the Commercially Important Squid, *Loligo pealei*.
• Behavioral and Hydrodynamic Components of Postlarval Bivalve Transport within Coastal Embayments.
• Molecular Biomarkers of Chemical Sensitivity.
• Biochemical Toxicology in Cetaceans.
• Identifying Wastewater-Derived Nitrogen in Aquatic Ecosystems Using Stable Isotope Tracers.
• Detection and Quantification of Live *Acanthamoebae* in Marine Ecosystems Using Molecular Genetic Methods.
• Molecular Biological Approaches for Non-Destructive Assessment of Chemical Effects on Marine Mammals.

In 1999, WHOI Sea Grant provided 21 months of support for graduate students through research awards and also sponsored Jennifer Arnold, a doctoral candidate at the University of Massachusetts–Boston, as a Dean John A. Knauss Marine Policy Fellow with the National Sea Grant College Program.

In terms of informal education, WHOI Sea Grant maintains close working relationships with the Massachusetts Marine Educators, the National Marine Educators Association, and the Woods Hole Science and Technology Education Partnership. At the local level, Sea Grant is an active participant in science fairs, with staff serving as project advisors and judges. Each year, top science fair winners are guest speakers at the opening night of the "Oceans Alive" lecture series. For the seventh consecutive year, WHOI Sea Grant sponsored "Sea Urchins," a summer program for children ages five to seven. Perhaps Sea Grant's most important contribution to education in our region is the provision of educational materials to numerous programs, including Children's School of Science, Cape Cod Children's Museum, Cape Cod Museum of Natural History, Association for the Preservation of Cape Cod, Cape Cod National Seashore, Wellfleet Audubon Sanctuary, New England Aquarium, Thornton W. Burgess Society, and school districts throughout southeastern Massachusetts and the world.

Transferring the results of research and providing general marine-related information are important components of the WHOI Sea Grant Marine Extension and Communications Program. Both programs facilitate communication among users and managers of marine resources, including members of the fishing community, aquaculturists, local officials, environmental regulatory agency managers, educators, and the general public. Two areas of particular interest in the marine extension program are coastal processes and fisheries and aquaculture.


George Hampson

Larry Costello, left, and Will Ostrom examine 18 months' growth on a "mussel sock" or collector at an experimental site off Martha's Vineyard for Sea Grant-sponsored work on a bioeconomic approach to offshore mariculture.

WHOI Sea Grant provides information to a broad audience through a variety of means, including Web sites. The WHOI Sea Grant Web site (www.whoi.edu/seagrant) provides access to information on current research and outreach projects and funding opportunities. In collaboration with other Sea Grant programs, we have developed two new Web sites:

• Marine Science Careers Web site (www.marinecareers.net) as a companion to the publication *Marine Science Careers: A Sea Grant Guide to Ocean Opportunities*, and
• the Northeast Regional Sea Grant Program Web site (web.mit.edu/seagrant/northeast) to highlight topics of interest throughout the northeast region.

Publications are another outreach vehicle for WHOI Sea Grant. Along with MIT Sea Grant, we publish the newsletter *Two if by Sea* three times each year. Our educational fact sheets called "Focal Points" are geared for legislators and coastal decision makers, and the "Marine Extension Bulletins" are designed for a more technical audience.

Sea Grant's low power radio program, Sound Waves, targeted at auto passengers traveling from Woods Hole to Martha's Vineyard by ferry, continued throughout 1999 and was selected for inclusion in an upcoming video highlighting innovative uses of low power radio as a communications tool.

—Judith E. McDowell, Sea Grant Coordinator

Dean's Report

The 1998 External Review of the Joint Program provided exceptional compliments about the Joint Program and also set forth some challenges to be met. During 1999, faculty, staff, and students in the Joint Program at WHOI and at MIT addressed these challenges. Actions taken to strengthen the program included:

• Improving financial support for graduate students with funding from both institutions in order to decrease the substantive graduate student burden on advisors' grants and contracts.

• Curriculum modifications to provide greater flexibility for physical oceanography students and revisions to the Student Guide for applied ocean science and engineering students.

• More attention to preparation of faculty for teaching, advising, and mentoring.

• Enhanced career counseling, including more formal feedback and participation from alumni and alumnae of the Joint Program.

The Report on the Response of the MIT/WHOI Joint Program to the External Review Committee reaffirmed the 1968 Memorandum of Understanding between MIT and WHOI that established the Joint Program. It notes that high quality education in oceanography and ocean engineering may well be more important today than it was in 1968:

> "Improved understanding of the oceans, and the interactions of the oceans with the atmosphere, with land, and with human civilizations is essential to inform policies that will ensure a better quality of life for present and future generations…
>
> "The combined faculties and resources of both institutions provide a breadth and depth of teaching, advising, research and mentoring in the major efforts underpinning advances in understanding the oceans: observation, experimentation, theory and modeling. This is stimulating to colleagues participating in the Joint Program at both institutions and simultaneously attracts the very best students to graduate study. In turn, in a powerful and positive synergy, these students add significantly to the intellectual vitality of both institutions. The contributions of the students and the graduates of the Joint Program add significantly to the national and international reputations of both institutions."

Twenty-six new students enrolled in the Joint Program, bringing total enrollment to 128 for fall 1999. Thirty-two new graduates (see box on degrees awarded) joined the alumni/ae body, which now numbers 580.

The international nature of our education programs was enhanced on July 21, 1999, when WHOI Director Bob Gagosian and University of Concepción Rector Sergio Lavanchy Merino signed a Memorandum of Understanding for cooperation between the two institutions to enhance graduate education and research in ocean sciences in Chile.

The postdoctoral program continues to attract excellent early career scholars to Woods Hole. In 1999, nine postdoctoral Scholars and one Marine Policy Fellow were selected from 119 applicants.

Thirty Summer Student Fellowships were awarded from an applicant pool of 255, with annual gifts and endowed funds supporting 15 fellowships and a grant from the National Science Foundation providing another 15 fellowships. Three Minority Traineeships were supported by endowed funds and the US Geological Survey, and 45 guest students were in residence during the summer of 1999. A summer lecture series sponsored by the

Tom Kleindinst

Students, friends, relatives, and Education Office staff gathered for an informal graduation celebration under a tent on the Quissett Campus in June 1999.

Education Office provides an introduction and overview of Institution research as well as a special ethics-in-science session. WHOI Scientific and Technical Staff members presented 27 of these talks during summer 1999.

The 41st Geophysical Fluid Dynamics Program summer session met at Walsh Cottage to consider "Stirring and Mixing" with 72 staff and visitors plus 10 Fellows at the graduate and postdoctoral levels. This program is funded by the National Science Foundation and the Office of Naval Research.

The Institution's long-standing tradition of support for science and mathematics in local schools continued in 1999. Activities in this arena include support of the Woods Hole Science and Technology Education Partnership (WHSTEP), countless volunteer efforts of WHOI employees that include serving as science fair advisors and judges, and scholarship prizes awarded at the Falmouth Academy and Falmouth Public Schools science fairs. In 1999, the scholarship offered to the overall winner of the Falmouth Public Schools science fair was named for Mary Sears in memory of her exceptional contributions to ocean sciences, the Institution, and the local community. In addition to an outstanding career as a perceptive WHOI scientist and rigorous scientific editor, Mary Sears served as a member of the Falmouth School Committee from 1952 to 1973, including nine years as committee chair. We were pleased to present the first Mary Sears Scholarship to Joe Rago.

Building on these local efforts, WHOI scientists and engineers initiated some new approaches to the Institution's contributions to the national K-12 science and math education effort. Debbie Smith, Associate Scientist in the Geology and Geophysics Department, shared the adventure of a research cruise she led to Puna Ridge off Hawaii through a World Wide Web site called "Voyage to Puna Ridge," and Senior Scientists Dan Fornari and Susan Humphris, also members of the G&G Department, launched another Web effort that invites students and the public to join several cruises to explore the earth's mid-ocean ridges.

Shelley Lauzon

Dean John Farrington, left, and David Game, Turnstone Publishing Group's Vice President of Internet Development, discuss Turnstone products during the National Science Teacher's Association spring 1999 meeting where the books and associated materials were introduced. Three of the Turnstone titles in the Ocean Pilot (grades 4–6) and Ocean Explorer (grades 6–8) series are shown above.

Two series of oceanography books targeted for children in grades four though eight were produced in 1999 through the collaborative efforts of Turnstone Publishing Group and the Woods Hole Oceanographic Institution. Published by Steck Vaughn, a subsidiary of Harcourt General, the titles in the Ocean Pilot series, for grades four to six, are *Benjamin Franklin and the Mysterious Ocean Highway*, *Off to Sea*, *Arctic Investigations*, and *Follow That Fin!* For grades six to eight, the Ocean Explorer series includes *Dive to the Deep Ocean*, *Ocean Detectives*, *Meteorite!*, and *Down to the Sunless Sea*. Associate Scientist Richard Norris, Curriculum Coordinator Katherine Madin, and Joint Program Graduate Amy Samuels authored three of these books, and many, many WHOI staff contributed to them.

Degrees Statistics

		1999	1968–99
WHOI	Ph.D.	0	4
MIT/WHOI	Ph.D.	18	376
MIT/WHOI	Sc.D.	1	31
MIT/WHOI	Engineer	1	55
MIT/WHOI	S.M.	9	110
MIT/WHOI	M.Eng.	1	4
Total Degrees Granted		30	580

The WHOI education programs and the Institution lost a valued participant and supporter in August with the tragic accidental death of Charley Hollister, Dean from 1979 to 1989. His infectious enthusiasm continues to influence ocean science research and education in many ways, especially through the careers of students he advised. We are grateful to the many contributors to a growing scholarship fund that will provide a permanent memorial to this special oceanographic educator.

—John W. Farrington, Associate Director for Education and Dean of Graduate Studies

Craig Dickson

Atlantis and Alvin spent 1999 in the Pacific largely working at hydrothermal vents.

R/V *Atlantis* & DSV *Alvin*

Total Nautical Miles in 1999—21,951
Total Days at Sea—287
Total Number of *Alvin* Dives—188

Atlantis crew and scientific party members welcomed 1999 at sea in the vicinity of Easter Island during studies of the ecology, biology, and geology of the "superfast" mid-ocean ridge spreading center along the Southeast Pacific Rise. Continuing the scientific community's effort to investigate global hydrothermal vents, the ship then moved to the East Pacific Rise at 18° South for work that included investigations of lava flows, geologic surveys with *ABE* (WHOI's Autonomous Benthic Explorer), and extensive mussel bed sampling. Other hydrothermal vent work during 1999 included investigations on the Juan de Fuca Ridge and studies under the Life in EXtreme ENvironments (LEXEN) and Larvae At Ridge VEnts (LARVE) programs on the East Pacific Rise.

During March and April, imaging, observation, and sampling of the uppermost oceanic crust exposed in the walls of the Hess Deep Rift centered at 2°N, 101°W were undertaken using the *DSL-120* and *Argo II* towed systems along with *Alvin*. Seamounts were also the object of *Atlantis*-based studies during the year. Two summer research voyages in the Gulf of Alaska examined the volcanic and tectonic evolution of the Patton-Murray seamounts along with their biological communities and methane seeps.

In September, *Atlantis* visited an instrumented Ocean Drilling Program borehole to collect data and recover instruments, and October work included sampling and photographing biotic communities based on whale carcasses on the seafloor as well as investigations at the San Clemente Seep and along the San Clemente Fracture Zone.

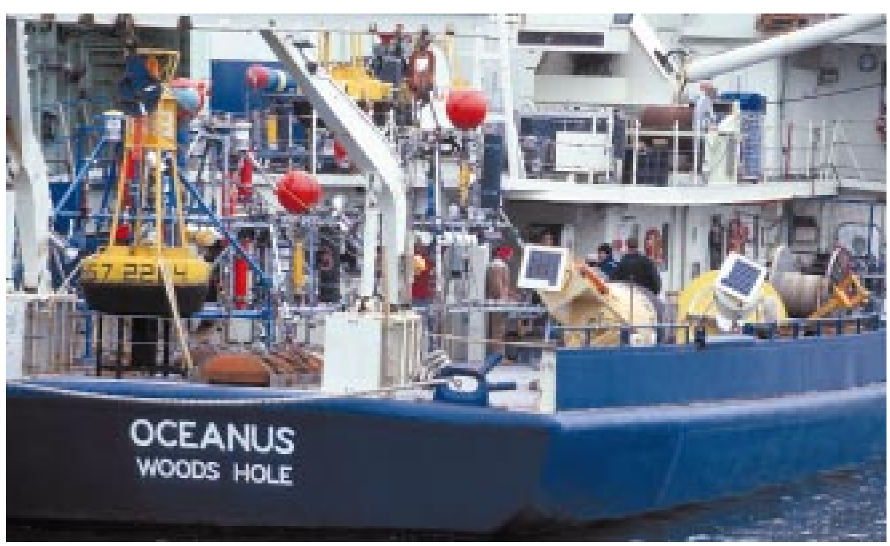
Further hydrothermal vent studies through December found the ship at sea again for part of the year-end holidays, concluding with arrival in San Diego on December 27.

Chief scientists for 1999 were: R. Vrijenhoek, Rutgers Univ. (Voyage 3, Leg XXX, with 15 *Alvin* dives); J. Sinton, Univ. of Hawaii (Leg XXXI, 23 dives); J. Karson, Duke Univ. (Leg XXXII, 15 dives); C. Fisher, Penn. State Univ. (Leg XXXIII, 13 dives; and Leg XXXVIII, 12 dives); C. Cary, Univ. of Delaware (Leg XXXIV, 22 dives); B. Carson, Lehigh Univ., and M. Torres, Oregon State Univ. (Leg XXXV, 15 dives) R. Duncan, Oregon State Univ. (Leg XXXVI, 8 dives); L. Levin, Scripps Inst. of Oceanography (Leg XXXVII, 14 dives); K. Becker, Univ. of Miami (Leg XXXIX, 15 dives); B. Walden (Leg XL, 1 dive); C. Smith, Univ. of Hawaii (Leg XLII, 7 dives); R. Lutz, Rutgers Univ. (Leg XLIII, 15 dives); and L. Mullineaux (Leg XLIV, 13 dives).*

R/V *Oceanus*

Total Nautical Miles in 1999—22,296
Total Days at Sea—180

Oceanus was a principal platform for GLobal Ocean ECosystems Dynamics (GLOBEC) investigations on Georges Bank. GLOBEC scientists staged some 100 research cruises from 1994 through 1999, largely using *Oceanus* and its sister ship *Endeavor* operated by the University of Rhode Island. Their objective was to develop a fundamental understanding of the underlying physical and biological processes that control the abundance of key populations, focusing



Tom Kleindinst

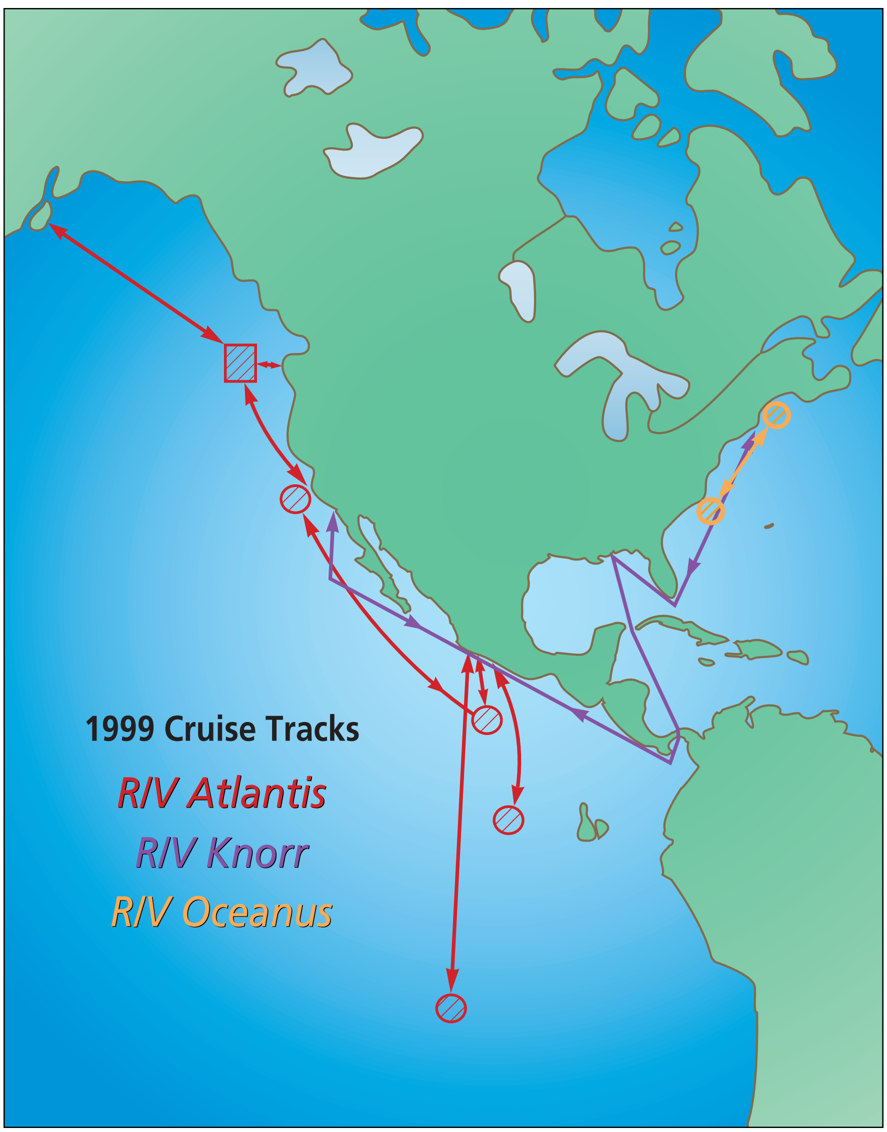
The Oceanus deck bristles with gear for December 1999 US Geological Survey work.

on certain species of fish and the zooplankton that are their primary food source. The field work generally included two approaches: 1) Broad-scale field surveys were structured to follow cod and haddock through their early larval stages with sampling and measurements at a grid of 50 to 80 stations occupied repeatedly during the six-year field program. 2) Process studies focused on both the links between the target species and on their physical environment. The GLOBEC work in 1999 extended from February through August and also took *Oceanus* to Georges Bank in November.

On September 8, *Oceanus* left Woods Hole to begin the Shoaling Waves Experiment to investigate wind input, surface dissipation, and directional properties of shoaling waves using air-sea interaction and acoustical spar buoys as well as directional wave rider moorings. When Hurricane Floyd headed for the study area located on the continental shelf around 36°N, 75° W, the ship took shelter in Boston Harbor. The shoaling wave work was taken up again in late October and December.

During September and early October, *Oceanus* was engaged in studies of metal speciation and cyanobacterial ecology in the Sargasso Sea and testing of an imaging-in-flow cytometer. In early December, deployment of a six-element moored array to investigate resuspension, transport, and deposition of sediments in the vicinity of the New York Bight was undertaken for a team of US Geological Survey scientists.

Chief scientists for 1999 were: M. Taylor, NOAA (Voyage 336), R. Limeburner (Voyages 337 & 345); J. Irish (Voyages 338, 344, & 346); R. Schlitz, NOAA (Voyage 339, 347, & 353); D. Hebert, URI (Voyages 340 & 343); C. Miller, Oregon State Univ. (Voyage 341); R. Houghton, Lamont-Doherty Earth Observatory (Voyage 342); H. Graber, Univ. of Miami (Voyages 348, 351, 352 & 355); J. Moffett (Voyage 349-I); K. Barbeau, US Geological Survey (Voyage 349-II); M. Sieracki, Bigelow Laboratory for Oceanography (Voyage 350); and B. Butman, US Geological Survey (Voyage 354).*



Jayne Doucette

Joanne Tromp

Snow blankets R/V Knorr at the WHOI pier.

R/V Knorr

Total Nautical Miles in 1999—13,060

Total Days at Sea— 61

This was a short operating year for *Knorr* as the ship was in lay-up status at the WHOI pier in the early and later months of 1999. On March 2, the ship traveled to Panama City, Florida, to mobilize for the U.S. Navy's "Kernal Blitz" exercise off San Diego. From then through early May, *Knorr* was engaged in equipment tests and other tasks for the Navy's Coastal System Station, returning to Woods Hole on May 12.

The Chief Scientist for Voyage 160, Legs I-IV, was C. Witten, Office of Naval Research.

*Gaps in cruise numbers generally indicate transits or short trips for engineering tests where no chief scientist was named.

Tom Kleindinst

Members and Trustees gathered in the Clark 5th floor conference room for their 1999 October meetings.

Tom Kleindinst

Trustees and Members of the Corporation shared lunchtime discussions at the May 1999 meetings. In the foreground, Senior Scientist Bob Beardsley discusses his work with Trustee Bill Kealy.

James Luyten
Senior Associate Director and Director of Research

John W. Farrington
Associate Director for Education and Dean of Graduate Studies

Richard F. Pittenger
Associate Director for Marine Operations

Daniel H. Stuermer
Director of Development

Honorary Members

Richard F. Alden
Los Angeles, CA

Marjorie Atwood
Newport, RI

Glenn W. Bailey
Hobe Sound, FL

George F. Bennett
State Street Investment Trust Boston, MA

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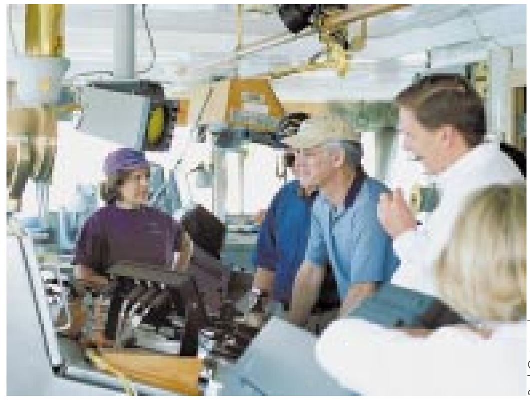

Rod Catanach

Secretary of the Navy Richard Danzig (tan cap) toured R/V Oceanus during a spring visit to WHOI. Associate Directors Jim Luyten, right, and Dick Pittenger flank the Secretary, and Andy Danzig is at left.

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The Hawaii 2 Observatory junction box goes over the side of R/V Thompson *(Univ. of Washington) during nighttime operations in the Pacific. Alan Chave was Chief Scientist.*

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Joint Program student Astri Kvassnes photographs seafloor samples in the McLean Lab atrium.

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Qiao Hu
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Heather L. Hunt
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Darlene R. Ketten
Associate Scientist

Tom Kleindinst

Geologist Henry Dick examines seafloor rock samples at the McLean Laboratory.

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Postdoctoral Investigator

Aishao Li
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Photos: Jayne Doucette

During the 11th annual Employee Recognition ceremony, the security guards represented by (top photo, left to right) Vasco Pires, Bill Sparks, and Allan Brierley, received the Penzance Award for overall exceptional performance, WHOI spirit, and contributions to the personal and professional lives of Institution staff. The Vetlesen Award for a variety of exceptional contributions to the WHOI community over a long period of time went to Aggie Collins, whose network installation work for the Computer and Information Services group has taken him to every WHOI office and attic, always with a big smile. Susan Mills received the Linda Morse-Porteous Award for leadership, mentoring, dedication to work and involvement in the WHOI community.

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Vicke Starczak, left, and Nan Trowbridge smile for the camera while conducting a flume study of the dispersal and settlement of marine larvae at RCRC.

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Craig E. Johnson
John N. Kemp
Jeffrey B. Lord
Christopher Lumping
Marguerite K. McElroy
Neil M. McPhee
George A. Meier
Charles J. Melchin
Marlene B. Messina
Stephen D. Murphy
Anita D. Norton
Gregory J. Packard
Stanley G. Rosenblad
David S. Schroeder
John J. Schwind, Jr.
William J. Sellers
John D. Sisson
Linda M. Skiba
Gary N. Stanbrough
Nancy W. Stedman
Nancy Y. Trowbridge
Karlen A. Wannop
Judith A. White

Biology Department

Nikolaus Abisla
Ellen Bailey
Nicoletta Biassoni
Iska Blusztajn
Mari Butler
Anne C. Canaday
Marjorie K. Clancy
Nancy J. Copley
Scott R. Cramer
Mary Ann Daher
Sheri D. DeRosa
Nancy A. DiMarzio
Christopher Franks
Diana G. Franks
Linda G. Hare
Andrew Girard
Kristin E. Gribble
David M. Kulis
Bruce A. Lancaster
Ethel F. LeFave
Jane E. Marsh
Susan W. Mills
Dawn M. Moran
Kristina M. Mullin
Samuel H. Patterson III
Rebecca Schaffner
Daniel W. Smith
Lisa G. Taylor
Mary Jane Tucci
Margaret M. Walden
Matthew Williams

Geology & Geophysics Department

Linda Angeloni
Andrew Aubrey
John W. Bailey
Ross Beaudette
Katherine W. Brown
Karen L. Coluzzi
Lori A. Dolby
David L. DuBois
Pamela V. Foster
C. Eben Franks
Charlene Gibson
Parker Hackett
C. Frances Halbrooks
Robert E. Handy
Seth H. Hitchings
Marleen H. Jeglinski
Janet M. Johnson
Huichan Lin
Karen Littlefield
Jill Murawski
Patricia Long
Teresa A. Norris
Julianne Palmieri
Kari Paro
Kira Pratt
Ellen R. Roosen
Brian Schroeder
Dana R. Stuart
Sean Sylva
Susan Trimarchi
Elaine A. Tulka
Shirley Waskilewicz
LuPing Zou

Marine Chemistry & Geochemistry Department

Tracy Abbruzzese
Rebecca A. Belastock
Scot P. Birdwhistell
L. Susan Brown-Leger
Sheila A. Clifford
Kate Doyle
Justin Dumouchelle
Hannah Gaines
Joanne E. Goudreau
Joanna F. Ireland
Judith Kelley
Kathleen Kucharski
Donna Mortimer
Melissa Peterson
Stephen Pike
Margaret M. Sulanowska
Carly H. Tarr
Max von der Heyt
Mary Zawoysky

Physical Oceanography

Eleanor M. Botelho
Kenton M. Bradshaw (LOA)
Nancy J. Brink
Margaret F. Cook
Lawrence P. Costello
Jane A. Dunworth-Baker
Penny C.Foster
Rosanna R. Fucile
Barbara Gaffron
Erica Greeley
Veta M. Green
Brian J. Guest
William H. Horn
George P. Knapp III
Ellen Levy
Mary Ann Lucas
Theresa K. McKee
Gail McPhee
Ann-Marie Michael
William M. Ostrom
Maren Plueddemann
John B. Reese
Hazel Salazar
Ryan Schrawder
Susan A. Tarbell
Robert D. Tavares
Deborah A. Taylor
Rochelle Ugstad
Brian S. Way
W. David Wellwood
Scott E. Worrilow
Jeanne A. Young
Marquerite E. Zemanovic

Tom Kleindinst

Mark St. Pierre works at the precision lathe in Clark Laboratory South.

Marine Policy Center

Andrew Beet
Gretchen McManamin
Mary E. Schumacher

Rinehart Coastal Research Center

John D. Sisson
Boat Operations and Senior Research Assistant I

Bruce A. Lancaster
CRL Operations and Senior Research Assistant I

Matthew R. Gould
Boat Operations Assistant and Engineering Assistant III

Olimpia L. McCall
Staff Assistant

Computer and Information Services

Michael Bishop
Bruce R. Cole
Edward F. Dow
Timothy Gage
Channing N. Hilliard, Jr.
Dennis Ladino
James MacConnell
David MacDonald
Clara Y. Pires

MBL/WHOI Library

Maureen E. Carragher
Barbara LaCasce
Lisa M. Raymond
Nancy Stafford

Administrative Staff

Deborah Aimone
Senior Acountant II

Nancy E. Barry
Assistant Human Resources Manager

Marie Basile
Procurement Representative II

Peggy A. Billings
Communications, Development, and Media Relations Administrator

Karin Bohr
Department Administrator, Physical Oceanography

Jane R. Bradford
Director of Planned Giving

Stella A. Callagee
Education Planning and Finance Administrator

Susan A. Casso
Department Administrator, Marine Chemistry and Geochemistry

Christine Charette
Development Officer

Linda L. Church
Accountant

Tracey Crago
Sea Grant Communicator

Vicky Cullen
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Mary Evans
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Maryanne F. Ferreira
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Susan Ferreira
Grants Administrator II

Danielle M. Fino
Web Communications Manager

Patricia A. Fisk
Administrator, Office Programs and Constituency Management

Karen E. Flaherty
Business Systems Representative

Larry D. Flick
Center Administrator, Deep Submergence Laboratory, and Security Officer

Annda W. Flynn
Center Administrator, Computer and Information Services

Dennis J. Fox
Procurement Manager

David G. Gallo
Director of Special Projects

Justine Gardner-Smith
Media Relations Officer

Ellen Gately
Center Administrator, Marine Policy Center

Arthur Gaylord
Computer and Information Services Director

Monika Grinnell
Senior Grants Administrator

K.I. Faith Hampshire
Center Administrator, Alvin *Group*

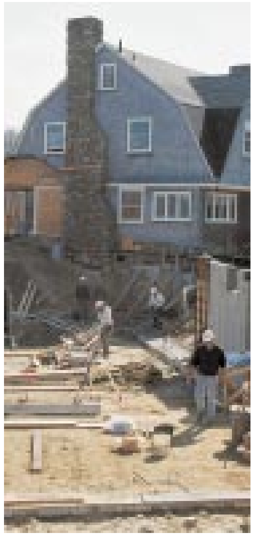
Susan K. Handwork
Center Administrator, National Ocean Sciences Accelerator Mass Spectrometry Facility

Frederic R. Heide
Manager, Graphic Services

Penelope Hilliard
Property Administrator

Kathleen Hudock
Administrator of Finance and Administration

Kevin F. Hudock
Benefits Manager



Photos: Tom Kleindinst

Three photos taken very early in the year, in July, and in November follow progress on the new wing for Fenno House through 1999. It accommodates the Director's suite and offices as well as conference facilities for Communications, Development, and Media Relations.

Richard B. Kendall
Procurement Representative II

Judith L. Kleindinst
Center Administrator, Biology

Kathleen P. LaBernz
Human Resources Manager

Michael P. Lagrassa
Assistant Procurement Manager

Shelley M. Lauzon
Media Relations Director

Laurence S. Lippsett
Science Editor

John Lombardi
Business Systems Representative

Katherine Madin
Curriculum Coordinator

Judith E. McDowell
Associate Dean

Stacey L. Medeiros
Controller

Joseph Messina III
Desktop Systems Analyst

Laura A. Murphy
Payroll Manager

Stephanie A. Murphy
Information Office and Exhibit Center Manager

Steven M. Murphy
Grants Administrator II

Thomas Nemmers
Department Administrator, Applied Ocean Physics & Engineering

Jane B. Neumann
Director of Principal Gifts

Catherine N. Norton
Director, MBL/WHOI Library

James Rakowski
Director of Major Gifts

Claire L. Reid
Executive Assistant to Director of Research

Leslie M. Reilly
Development Officer

Dena Richard
Assistant Payroll Manager

Peggy A. Rose
Executive Secretary to the Director

R. David Rudden, Jr.
Assistant Controller

Emily H. Schorer
Human Resources Administrator

Sandra A. Sherlock
Senior Procurement Representative

Marcella R. Simon
Registrar and Education Office Administrator

David Stephens
Manager of Accounts Receivable and Government Regulations

Michèle Stokes-Mattera
Institution Meetings and Office Systems Coordinator

Katrina A. Strozik
Management Information Services Manager

Daniel Stuermer
Director of Development

Maurice J. Tavares
Manager of Grants & Contracts

Julia G. Westwater
Associate Registrar

Mary Ann White
Travel Coordinator

William Wolf
Endowment and Finance Administrator

John A. Wood, Jr.
Procurement Representative II

Dianna M. Zaia
Manager of Treasury Operations

Administrative Support Staff

Pierrette M. Ahearn
Steven W. Allsopp
Mary Andrews
Lisa Arnold
Ellen M. Bailey
Linda Benway
Katherine Billings
Marsha Bissonette
Colleen Blanchard
Suzanne M. Bolton
Eleanor Botelho
Sandra L. Bothelho-Sherlock
Marilynn Brooks
Gail F. Caldeira
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Leonard Cartwright
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Katherine M. Davis
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Jayne H. Doucette
Stacey Drange
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Lynne M. Ellsworth
Glenn Enos
Janet Fields
Ruth E. Goldsmith
Pamela Goulart
David L. Gray
Deborah Hamel
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Jane A. Hopewood
Robin L. Hurst
Katherine Joyce
Thomas N. Kleindinst
Lynn Ladetto
Donna L. Lamonde
Samuel J. Lomba
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Jeanne Lovering
Richard C. Lovering
Molly M. Lumping
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Sandra E. Murphy
E. Paul Oberlander
Sharon Omar
Kathleen Patterson
Wendy Patterson
Isabel M. Penman
Jeanne A. Peterson
Jeannine M. Pires
John Porteous
Edward Reardon
Tariesa A. Reine
Tariesa J. Reine
Brenda M. Rowell
Timothy M. Silva
Anne Stone
June Taft
Mildred Teal
Judith A. Thrasher
Alison Tilghman
Susan Tomeo
Joanne Tromp
Rachelle Tucholke
Susan E. Vaughan
Robert J. Wilson

Facilities, Services, *Alvin* and Marine Operations Staff

Jonathan Alberts
Marine Operations Coordinator

Lawrence T. Bearse
Master, R/V Oceanus

Richard Chandler
Submersible Operations Coordinator

Ernest G. Charette
Assistant Facilities Manager

Gary B. Chiljean
Master, R/V Atlantis

Arthur D. Colburn III
Master, R/V Knorr

Joseph L. Coburn, Jr.
Ship Operations Manager

Stephen M. Faluotico
Deep Submergence Vehicle Pilot

Kevin Fisk
Chief Engineer, R/V Atlantis

Richard E. Galat
Facilities Engineer

Robert Greene
Distribution Manager

Matthew C. Heintz
Deep Submergence Vehicle Pilot

J. Patrick Hickey
Deep Submergence Vehicle Pilot

Lewis E. Karchner
Safety Officer

William N. Lange
Research Specialist

Barbara J. Martineau
Marine Operations Administrator

William E. McKeon
Facilities Manager

Theophilus Moniz III
Marine Engineer

Richard Morris
Chief Engineer, R/V Oceanus

David I. Olmsted
Boat Operator

Terrence M. Rioux
Diving Safety Officer

Manuel A. Subda
Marine Personnel Coordinator

Barrie B Walden
Manager, Operational Science Services

Steven Walsh
Chief Engineer, R/V Knorr

Robert A. Waters
Deep Submergence Vehicle Pilot

Ernest C. Wegman
Port Engineer

Robert L. Williams
Deep Submergence Vehicle Pilot

Facilities, Services, *Alvin*, and Marine Operations Support Staff

Michael T. Aiguier
Esmail Ali
John Allison
Douglas H. Andrews
Wayne A. Bailey
Coutenay Barber III
Linda J. Bartholomee
Harold A. Bean
Richard C. Bean
Jeffrey Benitz
Robert Bossardt
Thomas A. Bouche
John R. Bracebridge
Allan Brierley
John Broadford
Edmund K. Brown
Mark F. Buccheri
Barbara Callahan
Henry Carlisle
Richard Carter
John Cartner
Gary S. Caslen
John A. Cawley
Richard Chase
Margaret Crane
John Clement
Charles Clemishaw
Alberto Collasius, Jr.
Alden H. Cook
Torii M. Corbett
Marc A. Costa
John A. Crobar
Rowland Cummings
Judith O. Cushman
Sallye A. Davis
Elizabeth Delaney
Mark DeRoche
Jeffrey DeSouza
Craig D. Dickson
John Donovan
Mark Drewery
James H. Dufur, Jr.
William J. Dunn, Jr.
Geoffrey K. Ekblaw
Deidra L. Emrich
John Fetterman
Michael J. Field
Robert Flynn
Philip Forte
Damon Gayer
Joseph Giacobbe
Laura W. Goepfert
Edward S. Good
Allan G. Gordon
Edward F. Graham, Jr.
Jerry M. Graham
Billy Guest
Cecile Hall
William H. Handley
Patrick J. Harrington
Craig Henderson
Robert W. Hendricks
Patrick J. Hennessey
Marjorie M. Holland
Alan J. Hopkins
Sharon L. Hunt
Phillip M. Hurlbutt
J. Kevin Kay
Paul A. Kay
Fred W. Keller
Orville Kenerson
Raymond Kimball
Sara J. Kustan
James LaBreck
Robert S. Laird
Marc Leandro
Donald C. LeBlanc
Paul E. LeBlanc
Charles Lewis
Pete Liarikos
Jeffrey Little
Tim Logan
Glen R. Loomis
Brett Maloney
Piotr Marczak
Kenneth Martin
Paul Martin
Eduigez L. Martinez
Douglas L. Mayer
Joseph Mayes
Robert McCabe
Napoleon McCall, Jr.
Robert H. McMurray
Horace M. Medeiros
Anthony D. Mello
Antonio Mello
Mirth N. Miller
Maureen Moan
Patrick S. Mone
Christopher D. Morgan
Jaimie Morlett
Norman E. Morrison
Jose S. Mota
Jay R. Murphy
John R. Murphy, Jr.
Bruce Mushet
Matthew G. O'Donnell
David W. Olds
Charles A. Olson
Brian M. O'Nuallain
Griffith Outlaw
Stephen G. Page
Sheila T. Payne
David Peterson
Vasco Pires
Ed Popowitz
Douglas R. Quintiliani
Ken Rand
Dennis Reardon
John P. Romiza
James R. Ryder
Lewis J. Saffron
Michael J. Sawyer
Robert Schreiter
Emily Sheasley
Kent D. Sheasley
George P. Silva
David Sims
Daniel Slevin
Debra Snurkowski
Steven P. Solbo
William F. Sparks
Robert G. Spenle
Jeffrey M. Stolp
William Strickrott
Wayne A. Sylvia
Mark L. St. Pierre
William R. Tavares, Jr.
Anne M. Taylor
Kevin D. Thompson
Maeve Thurston
Anne Toal
Phil M. Treadwell
Herman Wagner
Colin Walcott
Robert Wichterman
Eileen R. Wicklund
Lance Wills
Kathleen D. Wilson
Carl O. Wood
Bonnie L. Woodward

1999 Retirees

Gunter H. Bauerlien
Patricia Brennan
Katherine Brown
C. Hovey Clifford
Aganoris Collins
James Craddock
William B. Cruwys
James A. Davis
Robert G. Drever
Daniel B. Dwyer
Arthur Gaines, Jr.
Channing N. Hilliard, Jr.
Dennis R. Lander
Daniel M. Lewis
Linda E. Lucier
Anita M. Palm
May A. Reed
David A. Ross
Edith H. Ross
R. David Simoneau
Geoffrey Thompson
N. Joye Wirsen

Tom Kleindinst

Jack Reese spray paints a winch part in the rigging shop of the Mooring Operations and Field Support Group.

Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography/Applied Ocean Science and Engineering

Doctor of Philosophy

Lihini I. Aluwihare
Mt. Holyoke College
Special Field: *Chemical Oceanography*
Dissertation: *High Molecular Weight Dissolved Organic Matter in Seawater: Chemical Structure, Sources and Cycling*

Jay A. Austin
California Polytechnic Institute, San Luis Obispo
Special Field: *Physical Oceanography*
Dissertation: *Wind-Driven Circulation on a Shallow, Stratified Shelf*

Natalia Y. Beliakova
Moscow State University
Special Field: *Physical Oceanography*
Dissertation: *Generation and Maintenance of Recirculations by Gulf Stream Instabilities*

Susan M. Bello
Michigan State University
Special Field: *Biological Oceanography*
Dissertation: *Characterization of Resistance to Halogenated Aromatic Hydrocarbons in a Population of* Fundulus herteroclitus *from a Marine Superfund Site*

Claudia R. Benitez-Nelson
University of Washington
Special Field: *Chemical Oceanography*
Dissertation: *Phosphorus Cycling in the Gulf of Maine: A Multi-Tracer Approach*

Sean M. Callahan
Princeton University
Special Field: *Biological Oceanography*
Dissertation: *The Quorum Sensing Regulon of* Vibrio fischeri: *Novel Components of the Autoinducer/LuxR Regulatory Circuit*

Michael Y. Chechelnitsky
Upsala College
Special Field: *Physical Oceanography*
Dissertation: *Adaptive Error Estimation in Linearized Ocean General Circulation Models*

Yuriy V. Dudko
Moscow Physical Technical Institute
Special Field: *Ocean Engineering*
Dissertation: *Analysis of Seismo-acoustic Emission from Ice Fracturing Events During SIMI '94*

Deborah M. Fripp
Stanford University
Special Field: *Biological Oceanography*
Dissertation: *Techniques for Studying Vocal Learning in Bottlenose Dolphins,* Tursiops truncatus

Deborah R. Hassler
University of Kansas
University of Georgia, MS
Special Field: *Marine Geology and Geophysics*
Dissertation: *Plume-Lithosphere Interaction: Geochemical Evidence from Upper Mantle and Lower Crustal Xenoliths from the Kerguelen Islands*

Kelsey A. Jordahl
Eckerd College
Special Field: *Marine Geology and Geophysics*
Dissertation: *Tectonic Evolution and Midplate Volcanism in the South Pacific*

Douglas P. Nowacek
Ohio Wesleyan University
Special Field: *Biological Oceanography*
Dissertation: *Sound Use, Sequential Behavior and Ecology of Foraging Bottlenose Dolphins,* Tursiops truncatus

Edward R. Snow
Cornell University
MIT/WHOI Joint Program, SM
Special Field: *Ocean Engineering*
Dissertation: *Advances in Grasping and Vehicle Contact Identification: Analysis, Design and Testing of Robust Methods for Underwater Robot Manipulation*

Mikhail A. Solovev
Moscow State University
Special Field: *Physical Oceanography*
Dissertation: *Assessment of Mesoscale Eddy Parameterizations for Coarse Resolution Ocean Models*

Tom Kleindinst

Dean John Farrington presides as Director Bob Gagosian and Associate Dean Judy McDowell present new graduate Kelsey Jordahl with the traditional graduate's plaque. Associate Registrar Julia Westwater is at right.

Brian J. Sperry
University of Iowa
Special Field: *Ocean Engineering*
Dissertation: *Analysis of Acoustic Propagation in the Region of the New England Continental Shelfbreak*

Louis C. St. Laurent
University of Rhode Island
Special Field: *Physical Oceanography*
Dissertation: *Diapycnal Advection by Double Diffusion and Turbulence in the Ocean*

Richard M. Wardle
University of York, UK
Special Field: *Physical Oceanography*
Dissertation: *Representation of Quasigeostrophic Eddies by a Potential Vorticity Flux*

Sandra R. Werner
Dartmouth College
Technical University of Aachen, Germany, MS
MIT/WHOI Joint Program, SM
Special Field: *Physical Oceanography*
Dissertation: *The Tidal Bottom Boundary Layer and the Wind-Driven Circulation on the Southern Flank of Georges Bank*

Doctor of Science

Steven R. Jayne
Massachusetts Institute of Technology
Special Field: *Physical Oceanography*
Dissertation: *Dynamics of Global Ocean Heat Transport Variability*

Master of Science

Katie Rose Boissonneault
University of Massachusetts, Dartmouth
Special Field: *Biological Oceanography*
Dissertation: *Microbial Food Web Interactions in Two Long Island Embayments*

Benjamin T. Gutierrez
College of William & Mary
Special Field: *Marine Geology and Geophysics*
Dissertation: *Relative Sea-Level Rise and the Development of Channel-Fill Sequences on Cape Cod, Massachusetts*

Michael J. Horowitz
Oberlin College
University of Massachusetts, Amherst
Special Field: *Marine Geology and Geophysics*
Dissertation: *Western South Atlantic Holocene and Glacial Deepwater Hydrography Derived from Benthic Formaniferal Cd/Ca and Stable Carbon Isotope Data*

Gwenaelle C. Jeunhomme
Ecole Nationale Superieure de Techniques Avancees, France
Special Field: *Physical Oceanography*
Dissertation: *Injection and Movement of Tritium-^{3}He in the Eastern North Atlantic*

Carlos H. Trevino
Instituto Technologico y de Estudios Superiores de Monterrey, Mexico
Special Field: *Physical Oceanography*
Dissertation: *Effects of the Chaotic Behavior of a Superposition of Waves in the Flux Across a Channel*

Caixia Wang
Ocean University of Qingdao, China
Ocean University of Qingdao, China, MS
Special Field: *Physical Oceanography*
Dissertation: *Diagnosis of Physical and Biological Controls on Phytoplankton Distributions in the Gulf of Maine–Georges Bank Region*

Qiang Wang
University of Science & Technology of China, Peoples Republic of China
Special Field: *Ocean Engineering*
Dissertation: *Underwater Object Localization Using a Biomimetic Binural*

Jonathan D. Woodruff
Tufts University
Special Field: *Ocean Engineering*
Dissertation: *The Contribution of High River Discharge Events to Deposition in the Lower Hudson River Estuary*

Kevin Xu
Harbin Shipbuilding Engineering Institute, Peoples Republic of China
Chinese Academy of Sciences, Peoples Republic of China, MS
Special Field: *Ocean Engineering*
Dissertation: *Maximum Likelihood Time-Domain Beamforming Using Simulated Annealing*

Master of Engineering

Rachel H. Levine
Wesleyan University
Special Field: *Ocean Engineering*
Dissertation: *Model of PAH and PCB Bioaccumulation in* Mya arenaria *and Application for Site Assessment in Conjunction with Sediment Quality Criteria*

Engineer's Degree

Benjamin K. Evans
Williams College
Special Field: *Ocean Engineering*
Dissertation: *The Effect of Coded Signals on the Precision of Autonomous Underwater Vehicle Acoustic Navigation*

MIT/WHOI Joint Program 1999–2000 Fall Term

AmyMarie Accardi
Rensselaer Polytechnic Institute

Robert P. Ackert
University of Maine
University of Maine, MS

Erik J. Anderson
Gordon College

Brian K. Arbic
University of Michigan

Juli K. Atherton
McGill University

Michael S. Atkins
University of California, Santa Cruz

Forest Atkinson
Reed College

Shannon M. Bard
Stanford University
University de Nantes, France

Kyle M. Becker
Boston University
Pennsylvania State University, MS

Mark D. Behn
Bates College

Bridget A. Bergquist
University of Wisconsin

Margaret S. Boettcher
Brown University

Katie R. Boissonneault
University of Massachusetts, Dartmouth

Juan Botella
La Universidad Autonoma de Baja California, Mexico
CICESE, Mexico, MSc

Melissa M. Bowen
Stanford University, BS, MS

Michael G. Braun
Brown University

Rosemarie E. Came
Boston College, BS, MS

Susan J. Carter
Harvard University

Mea Young Cook
Princeton University

Anna M. Cruse
University of Missouri, BS, MS

Heather E. Deese
Georgetown University

Amy G. Draut
Tufts University

Donald P. Eickstedt
Michigan Technological University
Johns Hopkins University, MS

Ryan M. Eustice
Michigan State University

Albert S. Fischer
Massachusetts Institute of Technology

Baylor T. Fox-Kemper
Reed College

Annette M. Frese
University of Connecticut, BS, MS

J. Steve Fries
Carnegie Mellon University

Heidi L. Fuchs
University of Wyoming, BS
University of Wisconsin, Madison, BS

Masami Fujiwara
University of Alaska, BA, MS

Alexandre S. Ganachaud
Université Paul Sabatier, France

Elizabeth D. Garland
Florida Institute of Technology

Geoffrey A. Gebbie
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Sam R. Geiger
Louisiana Technical University

Jennifer E. Georgen
University of Virginia, Charlottesville

Jason I. Gobat
Colorado School of Mines

Jared V. Goldstone
Yale University
Massachusetts Institute of Technology, SM

Christie L. Gow
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Carolyn M. Gramling
Florida International University

Rebecca E. Green
California Institute of Technology

Lara K. Gulmann
University of California, Berkeley

M. Robert Hamersley
University of Victoria, Canada
University of Calgary, Canada, ME

Jennifer A. Hammock
Massachusetts Institute of Technology

Heather M. Handley
James Cook University, Australia

Adam T. Harter
Yale University

Eli V. Hestermann
Purdue University

Mark F. Hill
University of Massachusetts, Boston, BS, MS

Fernanda G. Hoefel
Universidade Federal do Rio De Janeiro, Brazil, BS, MS

Allegra Hosford
Brown University

Robert M. Jennings
University of Michigan

Brenda A. Jensen
Eckerd College

Markus Jochum
Universitat Des Saarlandes, Germany

Linda H. Kalnejais
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Jody M. Katrein
Maine Maritime Academy

Robyn K. Kelly
University of South Carolina

Timothy C. Kenna
Vassar College

Daniel B. Kilfoyle
University of California, San Diego, MS
Massachusetts Institute of Technology, SB, SM

Vanya Klepac
Beloit College

Kenneth T. Koga
Rensselaer Polytechnic Institute

Jun Korenaga
University of Tokyo, Japan, BS, MSc

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Massachusetts Institute of Technology

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University of Bergen, Norway, BS, MS

Kirsten L. Laarkamp
Pennsylvania State University

Emily LeinonenDuFresne
Smith College

Xingwen Li
University of Science and Technology of China

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Universidad Politecnica de Catalunya, Spain, MS

William J. Lyons
Connecticut College
University of Wyoming, MS

Daniel G. MacDonald
University of New Hampshire

Matthew C. Makowski
State University of New York, Binghamton

Elizabeth L. Mann
Bowdoin College

Thomas Marchitto
Yale University

Sarah Marsh
Rice University

Sean P. McKenna
Rensselaer Polytechnic Institute

Amy R. McKnight
Colgate University

Patrick J. Miller
Georgetown University

Jennifer A. Munro
University of Massachusetts, Amherst, BSEE, MSEE

Rajesh R. Nadakuditi
Lafayette College

Payal P. Parekh
University of Michigan

Susan E. Parks
Cornell University

James W. Partan
University of Cambridge, UK

Yale J. Passamaneck
University of California, Santa Cruz

Ann Pearson
Oberlin College

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Nicole Poulton
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University of California, Davis

Tracy M. Quan
University of California, San Diego

Rebecca A. Rapoza
Dartmouth College
Humboldt State University, MA

Linda L. Rasmussen
California State University
New Mexico State University, MA

D. Benjamin Reeder
Clemson University

Matthew K. Reuer
Carleton College

Anna G. Rhodes
Massachusetts Institute of Technology

Gabrielle Rocap
Massachusetts Institute of Technology, SB, SM

Christopher N. Roman
Virginia Polytechnic Institute
University of California, San Deigo, MS

Hua Ru
Wu Han University, Peoples Republic of China
University of Houston, MS

Sarah L. Russell
Pomona College

James J. Ruzicka
Oregon State University
Univesity of Hawaii, MS

Alberto E. Saal
Massachusetts Institute of Technology
Universidad National de Cordoba, Spain, Ph.D.

Makoto Saito
Oberlin College

Paulo Salles
National Autonomous University of Mexico, Mexico

Mario R. Sengco
Long Island University, Southampton

William J. Shaw
Princeton University

Li Shu
The Cooper Union, BE, ME

Emily F. Slaby
Carnegie Mellon University

Luiz A. Souza
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Doherty Foundation Postdoctoral Scholar

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USGS Postdoctoral Scholar

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Devonshire Foundation Postdoctoral Scholar

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Exxon Foundation Postdoctoral Scholar

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Japan Society for the Promotion of Science Postdoctoral Fellow

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Roger Williams University

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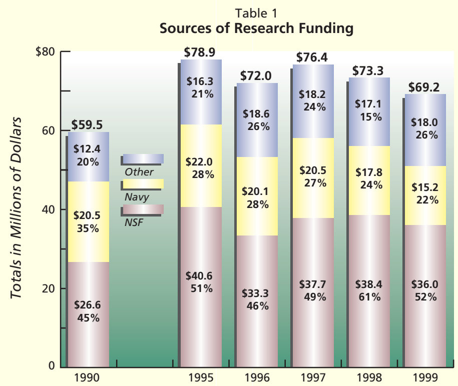
Massachusetts Institute of Technology

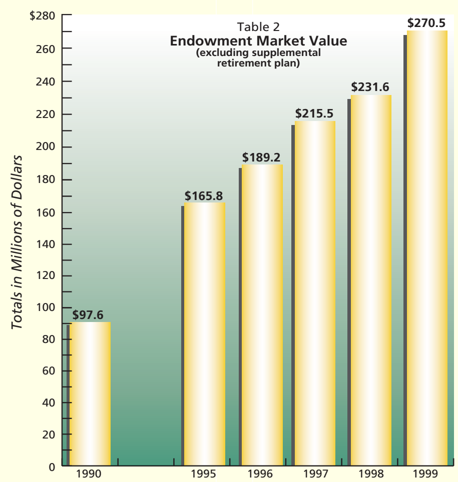
Financial Statements

The Woods Hole Oceanographic Institution has completed another successful year with full recovery of overhead, an increase in unrestricted net assets, and impressive growth of endowment. Including the net asset value of the defined benefit retirement plan (Note G), the Institution, for the first time, exceeded $500 million in total assets. The Institution's success was achieved in the face of another decline in government-sponsored research, a trend that has been occurring since 1997 but hopefully will reverse in 2000.

The financial markets continued strong during 1999 and WHOI's endowment increased in market value to $270.5 million compared to $231.6 million at the end of 1998. During 1998, investments in emerging markets and the transition to investing in alternative assets resulted in reduced returns; however, during 1999, WHOI's patience with its investment strategy resulted in a return of 19.5 percent.

For the first time, the financial statements include $3 million in long-term debt. The borrowings were used for the construction of the Fenno addition and a significant upgrade to the WHOI computer network infrastructure. The projects could have been funded internally, but the use of debt has a substantial financial benefit to WHOI based on the application of government regulations and the low cost of borrowing. It is anticipated that this round of borrowing will result in an additional $2 million in debt during 2000. The institution is embarking on a comprehensive campus planning effort, which may result in an aggressive construction schedule in future years, funded by additional tax-exempt debt.





Total sponsored research revenue was $69.2 million in 1999 compared with $73.3 million in 1998. The majority of the comparative decline resulted from a nonrecurring and non-overhead-bearing post-shakedown refit of *Atlantis* that occurred in 1998. Government sponsored research, excluding ship and submersible operations, was $45.6 million in 1999 compared to $46.3 million in 1998. Although these results represented declines of 6 percent and 2 percent, respectively, the Institution's labor bases, against which fringe benefits and overhead are recovered, finished the year ahead of budget, resulting in a modest over recovery of overhead expenses. Over recoveries are like "money in the bank" and help to reduce future overhead rates, contributing to WHOI's continued competitiveness. The Institution is in full compliance with all federal regulations, and, in 1999, for the fifth consecutive year, all government audits are current.

Unrestricted income from gifts and pledges was in excess of budget while the expense for "bridge support" that covers scientists' salaries between funding again came in under budget, contributing to the increase in unrestricted net assets. During 1999, the Institution used reserves, as planned, for the education program and for the operation of the Cotuit property.

Gifts, grants, and pledges from private sources totaled $9.4 million in 1999, making it the best noncampaign year ever. Previous to 1999, the best noncampaign year had been 1998 with $8.5 million. Outstanding pledges at the end of 1999 were $5.4 million, as compared to $4.8 million in 1998 and $3.8 million in 1997.

The transition to Year 2000 occurred without any noticeable impact on the Institution or its functions.

To remain competitive in both the conduct of research and graduate education to recruitment of the best scientists, research facilities must be replaced and modernized. An architectural firm has been hired to assist the Institution with the preparation of a master plan, and alternative financing plans are being developed. The planning process is made more complex by the disappointing trends in government research support, and, accordingly, WHOI must continue to build endowment, seek other sources of funding, aggressively pursue nongovernment projects, and generate unrestricted revenues from business development and other activities. Management is continuing to follow a strategy of improving service to science while reducing administrative costs. An "Internet strategy" has been developed that seeks to provide information, transactions, and services using the Internet and Intranet. The results have been very satisfactory, resulting in service improvements and labor and cost savings.

In summary, WHOI is building on the financial strength it has enjoyed for the past several years. Cost sharing on federal and foundation grants, the need for major new and renovated facilities, maintaining a state-of-the-art technology infrastructure, and funding the education program remain the biggest challenges.

—Paul Clemente, Associate Director for Finance and Administration

Statements of Financial Position as of December 31,1999

(with comparative information as of December 31, 1998)

	1999	1998
Assets		
Cash and cash equivalents:		
Operating	$10,304,606	$16,217,878
Sponsored research prepayment pool	607,163	1,694,628
Endowment	6,303,468	5,999,926
	17,215,237	23,912,432
Reimbursable costs and fees:		
Billed	1,925,005	1,146,056
Unbilled	3,775,094	3,689,810
Receivable for investments sold	152,708	1,279,721
Accrued interest and dividends	533,861	1,136,902
Other receivables	355,502	432,092
Pledges receivable	5,408,983	4,814,062
Inventory	808,919	692,957
Deferred charges and prepaid expenses	59,636	323,319
Investments, pooled	270,852,643	230,551,497
Investments, nonpooled	5,781,811	6,102,375
Prepaid pension cost	2,228,384	2,211,323
Supplemental retirement	7,733,931	6,892,383
Other assets	4,889,752	4,387,928
	321,721,466	287,572,857
Property, plant and equipment:		
Land, buildings and improvements	48,794,999	47,069,200
Vessels and dock facilities	2,654,406	2,754,406
Laboratory and other equipment	9,641,619	8,355,383
Construction in process	5,351,347	421,575
	66,442,371	58,600,564
Accumulated depreciation	(34,770,021)	(32,163,272)
Net property, plant and equipment	31,672,350	26,437,292
Remainder trusts	846,630	1,216,667
Total assets	$354,240,446	$315,226,816
Liabilities		
Accounts payable and other liabilities	$7,912,400	$8,903,204
Accrued payroll and related liabilities	5,298,557	4,824,765
Payable for investments purchased	-	2,845,856
Accrued supplemental retirement benefits	7,733,931	6,892,383
Deferred revenue and refundable advances	4,082,935	5,117,606
Deferred fixed rate variance	3,070,141	3,568,392
Loan payable	2,999,214	-
Total liabilities	31,097,178	32,152,206

Commitments and contingencies

Net Assets

	Unrestricted	Temporarily restricted	Permanently restricted		
Undesignated	$4,543,295	$		4,543,295	4,469,831
Designated	2,829,597	$ 4,907,217		7,736,814	6,868,599
Pledges		4,654,402	2,261,834	6,916,236	6,246,356
Plant and facilities	30,499,805	242,131		30,741,936	31,058,824
Education		2,679,119		2,679,119	2,859,995
Endowment and similar funds	68,501,035	164,709,242	37,315,591	270,525,868	231,571,005
Total net assets (Note B)	$106,373,732	$177,192,111	$39,577,425	323,143,268	283,074,610
Total liabilities and net assets				$354,240,446	$315,226,816

The accompanying notes are an integral part of these financial statements.

Statements of Cash Flows for the year ended December 31,1999

(with comparative information for the year ended December 31, 1998)

	1999	1998
Cash flows from operating activities:		
Total change in net assets	$40,068,658	$17,503,355
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	2,706,749	2,935,236
Net realized and unrealized gain on investments	(41,229,880)	(14,241,327)
Contributions to be used for long-term investment	(4,262,220)	(4,841,563)
(Increase) decrease in assets:		
Supplemental retirement	(841,548)	(695,287)
Accrued interest and dividends	603,041	(140,635)
Reimbursable costs and fees:		
Billed	(778,949)	1,136,208
Unbilled	(85,284)	49,066
Receivable for investments sold	1,127,013	-
Other receivables	76,590	(23,963)
Pledges receivable	(594,921)	(1,003,085)
Inventories	(115,962)	(52,340)
Deferred charges and prepaid expenses	263,683	(150,631)
Prepaid pension cost	(17,061)	(278,107)
Other assets	(501,824)	(28,046)
Remainder trusts	370,037	(41,576)
Increase (decrease) in liabilities:		
Accounts payable and other liabilities	(990,804)	(1,352,546)
Accrued payroll and related liabilities	473,785	(73,560)
Payable for investments purchased	(2,845,856)	1,416,897
Deferred revenue and refundable advances	(1,034,671)	(598,238)
Accrued supplemental retirement benefits	841,548	695,287
Deferred fixed rate variances	(498,244)	1,811,780
Net cash provided by (used in) operating activities	(7,266,120)	2,026,925
Cash flows from investing activities:		
Capital expenditures:		
Additions to property and equipment	(7,941,807)	(3,356,684)
Endowment:		
Proceeds from the sale of investments	126,094,954	464,439,261
Purchase of investments	(124,845,656)	(479,259,097)
Net cash (used in) investing activities	(6,692,509)	(18,176,520)
Cash flows from financing activities:		
Proceeds from loan payable	2,999,214	-
Contributions to be used for long-term investment	4,262,220	4,841,563
Net cash provided by financing activities	7,261,434	4,841,563
Net decrease in cash and cash equivalents	(6,697,195)	(11,308,032)
Cash and cash equivalents, beginning of year	23,912,432	35,220,464
Cash and cash equivalents, end of year	$17,215,237	$23,912,432

The accompanying notes are an integral part of these financial statements.

Statements of Activities for the year ended December 31, 1999

(with summarized financial information for the year ended December 31, 1998)

	Unrestricted					
	Operating	Sponsored Research	Temporarily Restricted	Permanently Restricted	1999	1998
Operating:						
Revenues:						
Fees	$294,132	$	$	$	$294,132	$373,399
Sponsored research:						
Government		58,747,647			58,747,647	62,809,830
Nongovernment		10,476,229	1,075,361		11,551,590	10,726,503
Sponsored research assets released to operations	69,223,876	(69,223,876)			-	-
Education:						
Tuition	2,335,701				2,335,701	2,652,371
Endowment income	3,183,141		1,275,385		4,458,526	3,676,520
Sponsored research	9,879				9,879	11,284
Gifts and transfers			597,886		597,886	867,189
Education funds released from restriction	2,054,147		(2,054,147)		-	-
Investment return designated for current operations	3,732,750				3,732,750	2,541,019
Contributions and gifts	2,038,038		1,256,786	3,549,486	6,844,310	6,563,933
Contributions and gifts released	-		(2,848,740)	2,848,740	-	-
Rental income	759,364				759,364	774,880
Communication and publications	207,211				207,211	318,615
Other	59,220				59,220	565,387
Total revenues	83,897,459	-	(697,469)	6,398,226	89,598,216	91,880,930
Expenses:						
Sponsored research:						
National Science Foundation	36,027,556				36,027,556	38,488,430
United States Navy	15,267,680				15,267,680	17,840,136
Subcontracts	5,356,734				5,356,734	5,835,413
National Oceanic & Atmospheric Administration	4,298,691				4,298,691	3,277,420
Department of Energy	653,341				653,341	778,412
United States Geological Survey	1,020,772				1,020,772	546,070
National Aeronautics & Space Administration	654,835				654,835	992,714
Other	5,944,267				5,944,267	5,514,756
Education:						
Faculty expense	2,303,217				2,303,217	2,238,580
Student expense	3,059,049				3,059,049	2,953,751
Postdoctoral programs	512,404				512,404	510,402
Other	540,347				540,347	495,287
Business development	92,119				92,119	527,467
Rental expenses	458,444				458,444	418,649
Communication publications and development	2,751,471				2,751,471	2,592,063
Unsponsored programs	2,867,766				2,867,766	2,178,658
Other expenses	1,868,945				1,868,945	1,670,942
Total expenses	83,677,638				83,677,638	86,859,150
Change in net assets from operating activities	219,821	-	(697,469)	6,398,226	5,920,578	5,021,780
Nonoperating income:						
Investment return in excess of amounts designated for sponsored research, education and current operations	8,148,762		26,299,144		34,447,906	11,978,925
Other nonoperating revenue	17,061		125,828		142,889	1,177,915
Nonoperating expenses:						
Other nonoperating expenses	200,776		241,939		442,715	675,265
Change in net assets from nonoperating activities	7,965,047		26,183,033		34,148,080	12,481,575
Total change in net assets	8,184,868		25,485,564	6,398,226	40,068,658	17,503,355
Net assets at beginning of year, as restated (Note B)	98,188,864	-	151,706,547	33,179,199	283,074,610	265,571,255
Net assets at end of year	$106,373,732	$ -	$177,192,111	$39,577,425	$323,143,268	$283,074,610

The accompanying notes are an integral part of these financial statements.

Report of Independent Accountants

To the Board of Trustees of Woods Hole Oceanographic Institution:

In our opinion, the accompanying statement of financial position and the related statements of activities and of cash flows present fairly, in all material respects, the financial position of Woods Hole Oceanographic Institution (the "Institution") as of December 31, 1999 and the changes in its net assets and its cash flows for the year then ended, in conformity with accounting principles generally accepted in the United States. These financial statements are the responsibility of the Institution's management; our responsibility is to express an opinion on these financial statements based on our audit. The prior year summarized comparative information has been derived from the Institution's 1998 financial statements, and in our report dated March 12, 1999, we expressed an unqualified opinion on those financial statements. We conducted our audit of these statements in accordance with auditing standards generally accepted in the United States, which require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements, assessing the accounting principles used and significant estimates made by management, and evaluating the overall financial statement presentation. We believe that our audit provides a reasonable basis for the opinion expressed above.

The financial statements for the years ended December 31, 1998 and 1997 have been restated as described in Note B.

PricewaterhouseCoopers LLP

March 10, 2000

A. Background

Woods Hole Oceanographic Institution (the "Institution) is a private, independent not-for-profit research and educational institution dedicated to working and learning at the frontier of ocean science and attaining maximum return on intellectual and material investments in oceanographic research located in Woods Hole, Massachusetts. The Institution was founded in 1930.

The Institution is a qualified tax-exempt organization under Section 501(c)(3) of the Internal Revenue Code as it is organized and operated exclusively for education and scientific purposes.

B. Summary of Significant Accounting Policies

Basis of Presentation

The accompanying financial statements have been prepared on the accrual basis and in accordance with the reporting principles of not-for-profit accounting as defined by Statement of Financial Accounting Standards ("SFAS") No. 116, *Accounting for Contributions Received and Contributions Made,* and No. 117, *Financial Statements of Not-for-Profit Organizations.* SFAS No. 116 requires that unconditional promises to give be recorded as receivables and revenues within the appropriate net asset category. SFAS No. 117 requires that the Institution display its activities and net assets in three classes as follows: unrestricted, temporarily restricted, and permanently restricted. Additionally, it requires the presentation of a statement of cash flows.

The financial statements include certain prior-year summarized comparative information, but do not include sufficient detail to constitute a presentation in conformity with generally accepted accounting principles. Accordingly, such information should be read in conjunction with the Institution's audited financial statements for the year ended December 31, 1998, from which the summarized information was derived.

Net assets, revenues, and realized and unrealized gains and losses are classified based on the existence or absence of donor-imposed restrictions and legal restrictions imposed under Massachusetts State law. Accordingly, net assets and changes therein are classified as follows:

Permanently Restricted Net Assets

Permanently restricted net assets are subject to donor-imposed stipulations that they be maintained permanently by the Institution. Generally the donors of these assets permit the Institution to use all or part of the income earned and capital appreciation, if any, on related investments for general or specific purposes.

Temporarily Restricted Net Assets

Temporarily restricted net assets are subject to donor-imposed stipulations that may or will be met by actions of the Institution and/or the passage of time. Unspent endowment gains are classified as temporarily restricted until the Institution appropriates and spends such sums in accordance with the terms of the underlying endowment funds at which time they will be reclassified to unrestricted revenues.

Unrestricted Net Assets

Unrestricted net assets are not subject to donor-imposed stipulations. Revenues are reported as increases in unrestricted net assets unless use of the related assets is limited by donor-imposed restrictions. Expenses are reported as decreases in unrestricted net assets. Gains and losses on investments and other assets or liabilities are reported as increases or decreases in unrestricted net assets unless their use is restricted by explicit donor stipulations or law. Expirations of temporary restrictions on net assets, that is, the donor-imposed stipulated purpose has been accomplished and/or the stipulated time period has elapsed, are reported as reclassifications between the applicable classes of net assets. Amounts received for sponsored research (under exchange transactions) are reflected in unrestricted sponsored research until spent for the appropriate purpose.

Contributions

Contributions, including unconditional promises to give, are recognized as revenues in the period received. Contributions subject to donor-imposed stipulations that are met in the same reporting period are reported as unrestricted support. Promises to give that are scheduled to be received after the balance sheet date are shown as increases in temporarily restricted net assets and are reclassified to unrestricted net assets when the purpose or items' restrictions are met. Promises to give, subject to donor-imposed stipulations that the corpus be maintained permanently, are recognized as increases in permanently restricted net assets. Conditional promises to give are not recognized until they become unconditional, that is, when the conditions on which they depend are substantially met. Contributions other than cash are generally recorded at market value on the date of the gift (or an estimate of fair value), although certain noncash gifts, for which a readily determinable market value cannot be established, are recorded at a nominal value until such time as the value becomes known. Contributions to be received after one year are discounted at the appropriate rate commensurate with risk. Amortization of such discount is recorded as additional contribution revenue in accordance with restrictions imposed by the donor on the original contribution, as applicable. Amounts receivable for contributions are reflected net of an applicable reserve for collectibility.

The Institution reports contributions in the form of land, buildings, or equipment as unrestricted operating support unless the donor places restrictions on their use.

Dividends, interest and net gains on investments of endowment and similar funds are reported as follows:

- as increases in permanently restricted net assets if the terms of the gift require that they be added to the principal of a permanent endowment fund;
- as increases in temporarily restricted net assets if the terms of the gift or the Institution's interpretation of relevant state law impose restrictions on the current use of the income or net realized and unrealized gains; and
- as increases in unrestricted net assets in all other cases.

Operations

The statements of activities report the Institution's operating and nonoperating activities. Operating revenues and expenses consist of those attributable to the Institution's current annual research or educational programs, including a component of endowment income appropriated for operations (see Note C). Unrestricted endowment investment income and gains over the amount appropriated under the Institution's spending plan are reported as nonoperating revenue as investment return in excess of amounts designated for sponsored research, education and current operations.

Cash and Cash Equivalents

Cash and cash equivalents consist of cash, money market accounts and overnight repurchase agreements with initial maturities of three months or less when purchased which are stated at cost, which approximates market value. At times the Institution maintains amounts at a single financial institution in excess of federally insured limits.

Included in cash at December 31, 1999 and 1998 is $607,163 and $1,694,628, respectively, representing advances received from the United States Navy and other U.S. Government and state agencies (the sponsored research prepayment pool). Such amounts are restricted as to use for research programs. Interest earned on unspent funds is remitted to the federal government. Cash and cash equivalents also include uninvested amounts from each classification of net assets (e.g., endowment).

Investments

Investment securities are carried at market value determined as follows: securities traded on a national securities exchange are valued at the last reported sales price on the last business day of the year; securities traded in the over-the-counter market and listed securities for which no sales prices were reported on that day are valued at closing bid prices. For investments in venture capital and investment partnerships, the Institution relies on valuations reported to the Institution by the managers of these investments except where the Institution may reasonably determine that additional factors should be considered.

Purchases and sales of investment securities are recorded on a trade date basis. Realized gains and losses are computed on a specific identification method. Investment income, net of investment expenses, is distributed on the unit method.

Options and Futures

An option is a contract in which the writer of the option grants the buyer the right to purchase from (call option) or sell to (put option) the writer a designated instrument at a specified price within a period of time. Premiums received on written options are recorded as negative cost basis until the contract is closed. The liability representing the Institution's obligation under a written option or the Institution's investment in a purchase option is valued at the last sale price or, in the absence of a sale, the mean between the closing bid and asked price or at the most recent asked price (bid for purchase option) if no bid and asked price are available. Over-the-counter written or purchased options are valued using dealer supplied quotations. Over-the-counter options have the risk of the potential inability of counterparties to meet the terms of their contracts. The Institution's maximum exposure for purchased options is limited to the premium initially paid.

A futures contract is an agreement between a buyer or seller and an established futures exchange or clearinghouse in which the buyer or seller agrees to take (or make) delivery of an amount of an item at a specific price on a specific date (settlement date). Upon entering into a futures contract, the Institution deposits with a financial intermediary an amount ("initial margin") equal to a percentage of the face value of the futures contract. Subsequent payments are made or received by the Institution each day, dependent on the daily fluctuations in the value of the underlying security, and are recorded as unrealized gains or losses. The Institution will realize a gain or loss equal to the difference between the value of the futures contract to sell and the futures contract to buy at settlement date or by closing the contract. Futures contracts are valued at the most recent settlement price.

Investment Income Utilization

The Institution's investments are pooled in an endowment fund and the investments and allocation of income are tracked on a unitized basis. The Institution distributes to operations for each individual fund an amount of investment income earned by each of the fund's proportionate share of investments based on a total return policy (a percentage of the prior three years' endowment market values).

The Board of Trustees has appropriated all of the income and a specified percentage of the net appreciation (depreciation) to operations as prudent considering the Institution's long and short-term needs, present and anticipated financial requirements, expected total return on its investments, price level trends, and general economic conditions. Under the Institution's current endowment spending policy, which is within the guidelines specified under state law, between 4 percent and 5.5 percent of the average of the market value of qualifying endowment investments at September 30 of each of the previous three years is appropriated. This amounted to $9,608,901 and $7,588,902 for the years ending December 31, 1999 and 1998, respectively, and is classified in operating revenues (research, education, and operations).

The Institution has interpreted relevant state law as generally permitting the spending of gains on endowment funds over a stipulated period of time.

Inventories

Inventories are stated at the lower of cost or market. Cost is determined using the first-in, first-out method.

Contracts and Grants

Revenues earned on contracts and grants for research are recognized as related costs are incurred.

Property, Plant and Equipment

Property, plant and equipment are stated at cost. Depreciation is provided on a straight-line basis at annual rates of 8 to 50 years on buildings and improvements, 28 years on vessels and dock facilities, and 3 to 5 years on laboratory and other equipment. Depreciation expense on property, plant, and equipment purchased by the Institution in the amounts of $2,605,973 and $2,834,460 in 1999 and 1998, respectively, has been charged to operating activities.

Depreciation on certain government-funded facilities (the Laboratory for Marine Science and the dock facility) amounting to $100,776 in 1999 and 1998, respectively, has been charged to nonoperating expenses as these assets are owned by the Government. There were no gains on the disposal of property, plant and equipment in 1999 and 1998.

Use of Estimates

The preparation of the financial statements in accordance with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and the disclosure of contingent assets and liabilities as of December 31, 1999 and 1998, as well as the reported amounts of revenues and expenses during the years then ended. Actual results could differ from the estimates included in the financial statements.

Reclassification of Amounts

Certain prior year amounts have been reclassified to conform to the December 31, 1999 presentation.

Restatement

In 1999, the Institution restated net assets as of December 31, 1997 to properly reflect pension and postretirement benefit costs in accordance with Statements of Financial Accounting Standards ("SFAS") No. 87, "Employers' Accounting for Pensions" and SFAS No. 106, "Employers' Accounting for Postretirement Benefits Other Than Pensions" and to properly reflect temporarily restricted investment income when earned in accordance with SFAS No. 117, "Financial Statements of Not-for-Profit Organizations." Prior to the restatement, the Institution recorded pension costs based on cash paid for employer contributions and recorded temporarily restricted investment income as deferred revenue until expenditures were incurred.

The effect of the restatement is presented below:

	Unrestricted net assets	Temporarily restricted net assets	Permanently restricted net assets	Total
Net assets at December 31, 1997, as previously reported	$92,625,768	$138,205,953	$29,237,444	$260,069,165
Recording of prepaid pension costs	1,933,216	-	-	1,933,216
Recording of temporarily restricted investment income	-	3,568,874	-	3,568,874
Net assets at December 31, 1997, as restated	$94,558,984	$141,774,827	$29,237,444	$265,571,255
Total change in net assets at December 31, 1998, as previously reported	$3,351,773	$9,668,738	$3,941,755	$16,962,266
Recording of prepaid pension costs	278,107	-	-	278,107
Recording of temporarily restricted investment income	-	262,982	-	262,982
Total change in net assets at December 31, 1998, as restated	$3,629,880	$9,931,720	$3,941,755	$17,503,355

C. Investments

The cost and market value of investments held at December 31 are as follows:

	1999		1998	
	Cost/(premium received)	Market	Cost/(premium received)	Market
U.S. Government and government agencies	$9,115,196	$8,649,788	$9,455,685	$9,569,265
Corporate bonds	23,495,708	22,190,605	15,655,157	16,014,417
Other bonds	6,259,492	5,923,533	5,374,862	5,093,275
Equity securities and mutual funds	99,099,911	135,345,966	100,109,271	123,803,114
International mutual funds	60,951,945	69,160,320	56,647,950	50,363,401
Venture Capital and Investment Partnerships	20,326,919	29,304,320	19,103,213	25,219,328
Other	325,729	325,729	1,121,854	1,284,992
Subtotal investments	219,574,900	270,900,261	207,467,992	231,347,792
Purchased call options	13,913	3,297	57,203	23,311
Written call options	(7,168)	(4,699)	(25,625)	(783,701)
Written put options	(15,188)	(46,216)	(21,000)	(35,905)
Total investments	$219,566,457	$270,852,643	$207,478,570	$230,551,497

Amounts held in Venture Capital and Investment Partnerships and other investments are invested in securities or other assets for which there is not necessarily a publicly-traded market value or which are restricted as to disposition. The return on such investments was $2,698,148 and $2,241,146 for the years ended December 31, 1999 and 1998, respectively, including dividends, distributions and changes in the estimated value of such investments.

At December 31, 1999, open future contracts sold short were as follows:

Futures	Expiration date	Aggregate face value	Market value
10 Year U.S. Treasury Note	3/22/00	$187,293	$181,875
30 Year U.S. Treasury Bond	3/22/00	$1,274,175	$1,246,172

The following schedule summarizes the investment return and its classification in the statements of activities:

	Unrestricted	Temporarily restricted	1999 Total	1998 Total
Dividend and interest income	$3,798,405	$1,275,385	$5,073,790	$6,715,677
Investment management costs	(1,075,321)	-	(1,075,321)	(692,340)
Net realized gains	2,612,445	10,404,176	13,016,621	36,155,279
Change in unrealized appreciation	12,318,291	15,894,968	28,213,259	(21,913,952)
Total return on investments	17,653,820	27,574,529	45,228,349	20,264,664
Investment return designated for:				
Sponsored research	(2,589,167)	-	(2,589,167)	(2,068,200)
Education	(3,183,141)	(1,275,385)	(4,458,526)	(3,676,520)
Current operations	(3,732,750)	-	(3,732,750)	(2,541,019)
	(9,505,058)	(1,275,385)	(10,780,443)	(8,285,739)
Investment return in excess of amounts designated for sponsored research, education and current operations	$8,148,762	$26,299,144	$34,447,906	$11,978,925

Endowment income is allocated to each individual fund based on a per unit valuation. The value of an investment unit at December 31, is as follows:

	1999	1998
Unit value, beginning of year	$3.9089	$3.6785
Unit value, end of year	4.5884	3.9089
Net change for the year	.6795	.2304
Investment income per unit for the year	.0824	.0868
Total return per unit	$ .7619	$ .3172

D. Pledges Receivable

Pledges receivable consist of the following at December 31:

	1999	1998
Unconditional promises expected to be collected in:		
Less than one year	$4,125,666	$2,615,729
One year to five years	1,283,317	2,198,333
	$5,408,983	$4,814,062

E. Deferred Fixed Rate Variance

The Institution receives funding or reimbursement from federal government agencies for sponsored research under government grants and contracts. The Institution has negotiated with the federal government fixed rates for the recovery of certain fringe benefits and indirect costs on these grants and contracts. Such recoveries are subject to carryforward provisions that provide for adjustments to be included in the negotiation of future fixed rates. The deferred fixed rate variance accounts represent the cumulative amount owed to or due from the federal government. The Institution's rates are negotiated with the Office of Naval Research (ONR), the Institution's cognizant agency.

The composition of the deferred fixed rate variance is as follows:

Deferred Fixed Rate Variance (liability), December 31, 1997	$(1,756,612)
1998 indirect costs	30,307,084
1998 adjustment	11,669
Amounts recovered	(32,130,533)
1998 (over)/under recovery	(1,811,780)
Deferred Fixed Rate Variance (liability), December 31, 1998	(3,568,392)
1999 indirect costs	33,084,491
Amounts recovered	(32,586,240)
1999 (over)/under recovery	498,251
Deferred Fixed Rate Variance (liability), December 31, 1999	$(3,070,141)

As of December 31, 1999, the Institution has recovered a cumulative amount in excess of expended amounts of $3,070,141 which will be reflected as a reduction of future year recoveries. This amount has been reported as a liability of the Institution.

F. Loan Payable

On May 27, 1999, the Institution entered into a $3,000,000 loan agreement with the Massachusetts Health and Educational Facilities Authority (the "Authority") to finance various capital projects. The loan matures on June 1, 2010. Interest is computed at a rate established by the Authority and this rate was 3.75% for the year ended December 31, 1999.

The loan agreement has covenants, the most restrictive of which requires the Institution to maintain unrestricted net assets at a market value equal to at least 1.0x outstanding indebtedness.

Principal payments during the term of the loan are as follows:

Year	
2000	$22,547
2001	47,524
2002	50,960
2003	54,644
2004	58,594
2005 and thereafter	2,764,945
Total	$2,999,214

G. Retirement Plans

The Institution maintains a noncontributory defined benefit pension plan covering substantially all employees of the Institution, as well as a supplemental benefit plan which covers certain employees. Pension benefits are earned based on years of service and compensation received. The Institution's policy is to fund at least the minimum required by the Employee Retirement Income Security Act of 1974.

	Qualified Plan Pension Benefits 1999	Qualified Plan Pension Benefits 1998
Change in Benefit Obligation		
Benefit obligation at beginning of year	$117,287,816	$107,000,311
Service cost	4,180,879	3,213,476
Interest cost	8,208,944	7,332,679
Amendments	10,584,215	-
Actuarial (gain)/loss	(17,180,701)	4,222,921
Benefits paid	(7,111,475)	(4,481,571)
Benefit obligation at end of year	$115,969,678	$117,287,816
Change in Plan Assets		
Fair value of plan assets at beginning of year	158,790,517	149,537,244
Actual return on plan assets	27,894,511	13,734,844
Benefits paid	(7,111,475)	(4,481,571)
Fair value of plan assets at end of year	$179,573,553	$158,790,517

	Qualified Plan Pension Benefits 1999	Qualified Plan Pension Benefits 1998
Funded status	$63,603,875	$41,502,701
Unrecognized actuarial (gain)/loss	(73,106,806)	(40,896,168)
Unrecognized portion of net obligation/(asset) at transition	(1,289,293)	(1,936,363)
Unrecognized prior service cost/(credit)	12,160,543	2,752,327
Net amount recognized	$1,368,319	$1,422,497
Amounts Recognized in the Statement of Financial Position Consist of:		
Prepaid benefit cost	$1,368,319	$1,422,497
Weighted-Average Assumptions		
Discount rate as of December 31	8.00%	6.75%
Expected return on plan assets for the year	10.00%	9.00%
Rate of compensation increase as of December 31	3.50%	4.50%
Components of Net Periodic Benefit Cost		
Service cost	$4,180,879	$3,213,476
Interest cost	8,208,944	7,332,679
Expected return on plan assets and reserves	(12,688,120)	(10,546,822)
Amortization of:		
transition obligation/(asset)	(647,070)	(647,070)
prior service cost/(credit)	1,175,999	311,982
actuarial loss/(gain)	(176,454)	-
Net periodic benefit cost/(income)	$54,178	$(335,755)

Effective January 1, 1999, the qualified plan was amended to improve benefits for service over 25 years, reduce the vesting period, expand the lump sum option and eliminate certain early retirement subsidies for newly hired employees.

	Supplemental Plan Pension Benefits 1999	Supplemental Plan Pension Benefits 1998
Change in Benefit Obligation		
Benefit obligation at beginning of year	$3,685,379	$3,576,307
Service cost	109,906	111,913
Interest cost	221,296	235,860
Actuarial (gain)/loss	(407,215)	127,325
Benefits paid	(332,342)	(366,026)
Benefit obligation at end of year	$3,277,024	$3,685,379
Change in Plan Assets		
Fair value of plan assets at beginning of year	$ -	$ -
Employer contribution	332,342	366,026
Benefits paid	(332,342)	(366,026)
Fair value of plan assets at end of year	$ -	$ -
Funded status	(3,277,024)	(3,685,379)
Unrecognized actuarial (gain)/loss	(524,676)	(254,120)
Unrecognized portion of net obligation/(asset) at transition	256,950	385,907
Net amount recognized	(3,544,750)	(3,553,592)
True up to earmarked reserves	(4,189,181)	(3,338,791)
Total earmarked reserves	$(7,733,931)	$(6,892,383)
Amounts Recognized in the Statement of Financial Position Consist of:		
Accrued benefit liability	$(7,733,931)	$(6,892,383)
Weighted-Average Assumptions		
Discount rate as of December 31	8.00%	6.75%
Expected return on plan assets for the year	10.00%	9.00%
Rate of compensation increase as of December 31	3.50%	4.50%
Components of Net Periodic Benefit Cost		
Service cost	$109,906	$111,913
Interest cost	221,296	235,860
Expected return on plan assets and reserves	(291,188)	(281,087)
Amortization of:		
transition obligation/(asset)	128,957	128,957
actuarial loss/(gain)	(11,375)	(1,280)
Net periodic benefit cost/(income)	157,596	194,363
Investment return on invested reserves	165,904	154,530
Total periodic cost	$323,500	$348,893

The earmarked reserves are matched by a "Rabbi" Trust with $7,733,931 and $6,892,383, respectively as of December 31, 1999 and 1998.

H. Other Postretirement Benefits

In addition to providing retirement plan benefits, the Institution provides certain health care benefits for retired employees and their spouses. Substantially all of the Institution's employees may become eligible for the benefits if they reach normal retirement age (as defined) or elect early retirement after having met certain time in service criteria.

	Other Postretirement Benefits 1999	1998
Change in Benefit Obligation		
Benefit obligation at beginning of year	$21,998,913	$18,675,643
Service cost	490,210	441,396
Interest cost	1,420,108	1,295,184
Plan participants' contributions *	-	-
Actuarial (gain)/loss	(4,091,749)	2,340,048
Benefits paid net of plan participants' contributions	(787,039)	(753,358)
Benefit obligation at end of year	$19,030,443	$21,998,913
Change in Plan Assets		
Fair value of plan assets at beginning of year	13,701,233	11,621,126
Actual return on plan assets	2,021,124	1,879,465
Employer contribution	930,995	954,000
Plan participants' contributions *	-	-
Benefits paid net of plan participants' contributions	(787,039)	(753,358)
Fair value of plan assets at end of year	$15,866,313	$13,701,233

* plan participants' contributions are netted out of benefit claims

	1999	1998
Funded status	$(3,164,130)	$(8,297,680)
Unrecognized actuarial (gain)/loss	(2,859,332)	1,876,007
Unrecognized portion of net obligation/(asset) at transition	11,096,143	11,949,692
Unrecognized prior service cost/(credit)	(4,212,616)	(4,739,193)
Net amount recognized	$860,065	$788,826
Amounts Recognized in the Statement of Financial Position Consist of:		
Prepaid benefit cost	$860,065	$788,826
Weighted-Average Assumptions		
Discount rate as of December 31	8.00%	6.75%
Expected return on plan assets for the year	10.00%	9.00%

For measurement purposes, a 7.0% and 5.5% annual rate of increase in the per capita cost of covered healthcare benefits was assumed in 2000 for pre-65 and post-65 benefits, respectively.

These were assumed to decrease gradually to 4.5% and 5.0% respectively, and remain at that level thereafter.

	1999	1998
Components of Net Periodic Benefit Cost		
Service cost	$490,210	$441,396
Interest cost	1,420,108	1,295,184
Expected return on plan assets and reserves	(1,377,533)	(1,051,904)
Amortization of:		
transition obligation/(asset)	853,549	853,549
prior service cost/(credit)	(526,577)	(526,577)
Net periodic benefit cost/(income)	$859,757	$1,011,648

Assumed health care cost trend rates have a significant effect on the amounts reported for the health care plan. A one-percentage-point change in assumed health care cost trend rates would have the following effects:

	1-Percentage Point Increase	1-Percentage Point Decrease
Effect on total of service cost and interest cost	$352,914	$(277,215)
Effect on the postretirement benefit obligation:	2,885,965	(2,342,592)

I. Commitments and Contingencies

The Defense Contract Audit Agency (DCAA) is responsible for auditing both direct and indirect charges to grants and contracts on behalf of the ONR. The Institution and the ONR had settled the years through 1998. The current indirect costs recovery rates, which are fixed, include the impact of prior year settlements. While the 1999 direct and indirect costs are subject to audit, the Institution does not believe settlement of this year will have a material impact on its results of operations (change in net assets) or its financial position.

The Institution through its endowment fund is committed to invest $26,000,000 in certain venture capital and investment partnerships.

The Institution is a defendant in a legal proceeding incidental to the nature of its operations. The Institution believes that the outcome of these proceedings will not materially affect its financial position.