1997—what a year for the Woods Hole Oceanographic Institution! The events highlighting the new ship *Atlantis* brought a truly special pride in oceanography and a wonderful opportunity to present WHOI's excellent science, engineering, and education capabilities. Through these events, we renewed existing ties, made new friends, and brought ocean science personally to groups of both students and teachers. Hosting dignitaries in Pascagoula Mississippi, before the ship's maiden voyage, introducing employees as well as Trustees and Corporation Members to the ship in Woods Hole, and staging marathon events in both New York and Washington, DC, elicited a team effort across the Institution that was most gratifying. Special thanks go to everyone who contributed—and that includes nearly every group and department!

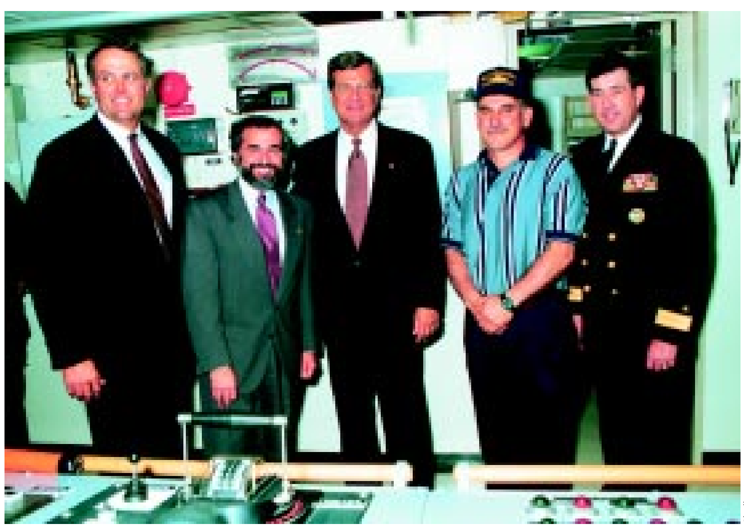
Tom Kleindinst

It was a happy day for Director Bob Gagosian, and all of us, when we welcomed the new Research Vessel *Atlantis* to Woods Hole on April 11, 1997.

The *Atlantis* events, particularly the Washington visit, were purposefully structured around WHOI's three basic premises: 1) What is good for the ocean sciences community and the federal agencies that fund the community's work is good for WHOI, 2) the ocean sciences community must continue to educate the public about using the oceans wisely, not just protecting them, and 3) the exploratory and discovery nature of ocean sciences makes them an excellent vehicle for introducing and engaging the public and the Congress to the value of science and engineering research and education as an investment in this country's future.

Staging the *Atlantis* events focused our organizational need for coordination of various communications and outreach activities. Consequently, the Associate Director for Communications and Development position was created, and Jacqueline Hollister was named to the new position in July. Jacquie joined the Institution as Director of Development in 1989, directed our most successful Capital Campaign, and served as overall chair of the *Atlantis* events. Jane Neumann, Director of Individual Gifts, was promoted to Director of Development in July, and, as we continued to review our outreach needs, Pam Hart, Executive Assistant to the Director, took on the responsibility of coordinating our efforts in Washington and working closely with our Associate Directors and Washington consultants to see that we take full advantage of opportunities there to raise the visibility of ocean sciences.

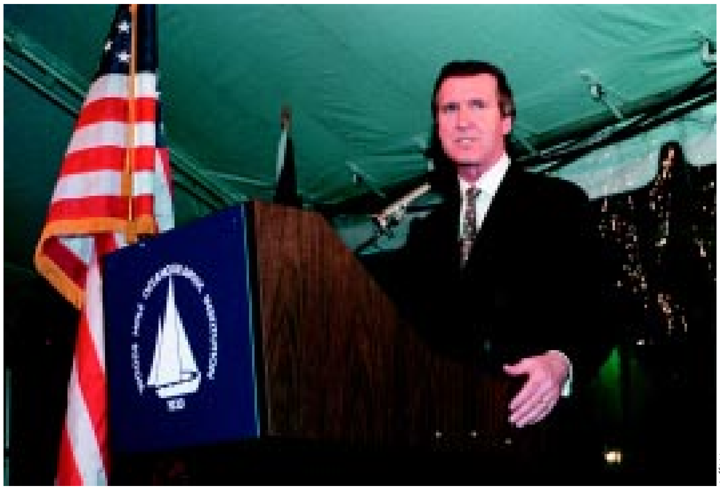
This functional consolidation brought together all our communications efforts to provide consistent image, focus, and strategy for the staffs of the Institution development, media relations, information, publications, and graphics services groups. These groups are managing several new endeavors that include television projects such as two Public Broadcasting System "Visionaries" segments featuring WHOI and a several-part television series that uses the Institution as a springboard for presenting ocean science research more generally. We are also working on a traveling museum exhibit with BBH Exhibits, Inc., and we have formed an educational communications alliance with Turnstone, Inc., which will begin producing oceanographic books, videos, and curricular materials aimed at the fourth to sixth grade and seventh to ninth grade levels in 1998 and plans to expand later to younger and older age groups.



Shelley Lauzon

Before *Atlantis* left Halter Marine in Pascagoula, Mississippi, on March 25, 1997, Director Bob Gagosian and Captain Gary Chiljean (striped shirt) were hosts aboard ship to, from left, President of Halter Marine Group, Inc. John Dane, Mississippi Senator and Senate Majority Leader Trent Lott, and Rear Admiral Paul G. Gaffney II, Chief of Naval Research.

The year gave us time to reflect on the success of the recent Capital Campaign (see Box overleaf) and to consider new directions for our Development efforts. Over the five and half years of the Capital Campaign, we raised $54 million with the roughly $10 million annual amount split about $6 million for endow-


Jeff Watts

Secretary of Defense William S. Cohen was among the speakers at a WHOI pierside reception for delegates to the Global Conference of the Advisory Committee on the Protection of the Sea during the R/V *Atlantis* visit to Alexandria, Virginia, May 18–21, 1997.

ment and $4 million for immediate needs. Nongovernment support for research and education totaled just under $6 million in 1992 and more than $8 million in 1997. Fund raising priorities set during the Capital Campaign fall into three categories: support for scientific and senior technical staff, education funding, and discretionary monies. Some specific Campaign benefits include:

• Beginning in 1995, we were able for the first time to offer one month of Institution support for Assistant Scientists, providing some relief from proposal pressure to those just setting the course for their careers. In 1997, this was extended to two months' support in the second and third years.

• The number of chairs awarded to WHOI Senior Scientists increased from 5 to 11 between 1992 and 1997, and annual funding for them increased from some $240,000 to nearly $600,000. Two new chairs awarded in 1997 were the Paul M. Fye Chair, awarded to Jack Whitehead of the Physical Oceanography Department, and the Edward W. and Betty J. Scripps Chair, awarded to Mark Kurz of the Marine Chemistry and Geochemistry Department. These chairs offer Senior Scientists some leverage and support to investigate areas they choose to explore, rather than areas the funding agencies want to fund.

• Three internal award programs contributed more than $800,000 to innovative scientific and technical staff efforts in 1997. One of these provides about $200,000 each year to encourage collaboration among scientists and engineers. These programs have been steadily growing over the past several years and are now supported at four times the 1992 level.

• The Senior Technical Staff Awards were established in 1995 to recognize excellence in engineering and instrument development. Based on their success, in 1997 we endowed two of these awards in memory of Allyn Vine and William (Skip) Marquet.

• As a result of the Capital Campaign, annual private funding for education increased about 20 percent, which includes a 40 percent boost for faculty support and allows us to offer 18-month rather than 12-month postdoctoral appointments.

• The Director's Discretionary Fund doubled during the campaign. These monies provide support for worthy scientific projects that may not have reached a stage to be attractive for government support, for purchase of equipment, for special incentives needed to recruit top-notch staff, for postdoctoral support, and for cost sharing—leveraging government awards that require matching institutional funds.

Capital Campaign Results

Research Support	$19,764,540
Scientific Staff Salaries	$10,126,507
Education Funds	$4,938,337
Unrestricted Monies	$19,250,755
	$54,080,139

All of these activities have resulted in strengthening the scientific staff, enhancing the vibrancy of our scientific community, and ensuring that we attract the best graduate students and postdoctoral candidates.

During 1997, we began to think strategically, to look ahead five to ten years, to construct a plan. The goals of supporting both people and scientific projects set during the Capital Campaign continue as the cornerstone of our private fund raising efforts, and we are also including some capital projects as a result of consultations with each scientific department regarding their needs.

I reflect on four years as Director of the Woods Hole Oceanographic Institution with an overwhelming sense of pride in challenges met, forward steps taken, and a cautiously bright outlook for the future of US ocean science. It was a great personal pleasure for me to welcome national leaders, Institution friends, and WHOI staff aboard the new ship *Atlantis* in the spring of 1997. Participating in the development of the "Visionaries" show on the Institution reminded me of the high quality and personal dedication of our personnel in all walks of Institution life. I believe that we have laid a firm foundation of excellent science, public and private fundraising success, and the best in human resources in order to move confidently toward the new millennium. It is a very exciting time.

—Robert B. Gagosian, Director


Jeff McEvoy

Congressman Jerry Lewis and Arlene Lewis (white jacket), the Congressman's administrative assistant, were among the guests Bob and Susan Gagosian welcomed to *Atlantis* during the ship's Alexandria/Washington, DC, port call.

Much of the observational work in the ocean sciences over the past decade has been associated with the US Global Change Research Program. Its individual components, such as the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), are tightly coordinated, multi-investigator research efforts requiring extensive planning and program review. This change in the style of conceiving, developing, and carrying out field programs from largely single investigator driven efforts to the large panel and steering committee approach has altered the sociology of ocean sciences.

When this cycle of Global Change Research programs was first envisioned in the 1970s and early 1980s, the fundamental ideas were that ocean processes are global in nature and that the ocean science disciplines are interrelated and interdependent—understanding the basic workings of the ocean thus requires interdisciplinary approaches. Routine satellite views and observations of the earth illustrated and reinforced this global view. Programs funded through the Global Change Research Program all comprise a mixture of global observations and special field programs designed to observe and understand localized or regional phenomena.

The World Ocean Circulation Experiment completed its field program in October 1997 with an R/V *Knorr* cruise from Ponta Delgada, Azores, to Woods Hole, and the Joint Global Ocean Flux Experiment completes its final cruise in the Southern Ocean in April 1998. Both programs are beginning a period of intense synthesis and modeling, to explore and understand the tremendous wealth of exciting data collected over the past ten years of field work. All of the global programs have yielded significant and often startling observations—some made in areas where little or no previous work had been done. We have a much deeper understanding of both the universality of many ocean processes, and of constraints that foster special states or restrict circulation in such areas as the Arabian Sea or southern ocean.

Institution scientists have played important roles in all phases of these global change research programs, and indeed much of the

Shelley Lauzon

Senior Associate Director and Director of Research Jim Luyten describes ocean current pathways to two young visitors during the *Atlantis* visit to New York.

Global Change Research

The US Congress enacted the 1990 Global Change Research Act to meet the need for a better understanding of the natural variability of Earth's global environment and the effects of human activity. It called for an integrative research effort "aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, [and] to promote discussion toward international protocols in global change research." This led to establishment of the US Global Change Research Program (USGCRP) as a Presidential Initiative. The program is coordinated across Federal agencies by the Subcommittee for Global Change Research (SGCR) of the Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council (NSTC).

The agencies involved in the program are:

- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- Department of Energy (DOE)
- Department of Commerce's National Oceanic and Atmospheric Administration (NOAA)
- Department of Agriculture (USDA)
- Environmental Protection Agency (EPA)
- Department of Defense (DoD)
- Department of Health and Human Services, National Institutes of Health
- Smithsonian Institution (SI)

These agencies work together to develop programmatic activities that respond to one or more of the following general focal areas of research:

- to observe and record what is happening to Earth's environment,
- to understand why changes are occurring,
- to improve predictions of what will happen in the future,
- to understand and estimate what global environmental change will mean for ecosystem and societal support systems, and
- to develop the tools needed by policy and decision makers to evaluate the consequences of different actions.

Roger Archibald

Will Ostrom steadies the surface mooring for a Pan-American Climate studies mooring being launched in the Pacific from R/V *Roger Revelle* (Scripps Institution of Oceanography).

surprising increase in the Institution's revenues during 1997 is associated with the extraordinary level of field work completed during 1997, including more than four months of R/V *Knorr* time devoted to WOCE related work. The WOCE Hydrographic Programme office, headed by Senior Scientist Terry Joyce, was located at WHOI as was the JGOFS national administrative office, with several WHOI people taking key roles. Senior Scientist Sus Honjo was chief scientist both for the first JGOFS cruise, aboard *Atlantis II* in March and April 1989, and the last, aboard *Nathaniel B. Palmer* (National Science Foundation) in Antarctic waters from late February to early April 1997. We anticipate continuing to play an important role in the analysis and modeling phases of these programs.

As this analysis phase begins, the community is also initiating planning for the next phase of field work and oceanographic research. During the past year, the Ocean Sciences Division of the National Science Foundation convened a workshop in each of the major disciplines that comprise the ocean sciences to discuss future directions. Results from these workshops are still being assimilated, and are expected to help shape the programs for the next decades. There has been an intense planning effort within the climate research community for the next generation of research programs designed to understand and predict climate change. Much of this is driven from the meteorological community, but the understanding that the ocean plays a fundamental role in mediating long-term climate change is well accepted. Indeed the intense attention given to El Niño has cemented the idea in the public mind that the ocean is important to Earth climate. Whatever specific programs appear under the guise of the Global Ocean Observing System and the Global Climate Research Program will have strong couplings to international meteorological community efforts, and providing appropriate data to initialize and validate global numerical models will be a central focus.

Other components of the Global Change Research Program are still in their observational phases. For example, intensive field work on Georges Bank for the Global Ocean Ecosystems Dynamics Program, GLOBEC, occupied nearly half of R/V *Oceanus*'s time at sea in 1997.

In all of these research efforts, there is an increasing need to establish and maintain sites for collecting high-quality, long-term, uninterrupted observations of ocean parameters. This will require ocean observatories similar to the ocean weather stations established in the early part of this century and now largely abandoned. Without an adequate baseline, it will be difficult to make quantitative estimates of long-term climate variability, and the extent to which these changes can be associated with anthropogenic influence.

Major efforts are underway in the ocean science community to develop and establish several ocean observatories to provide these essential baseline observations. While ultimately these monitoring programs will need to be supported through mission agencies, such as the National Oceanic and Atmospheric Administration, their design and integration into an observing network is a challenging problem for the research community.

—James Luyten, Senior Associate Director and Director of Research

Charley Hollister

Kathy Peroff of the Office of Management and Budget, WHOI Corporation President Jim Clark, and Jim Luyten are at the *Atlantis* rail as the ship steams into Alexandria, Virginia.

The Applied Ocean Physics & Engineering (AOP&E) Department, with 156 staff members and 28 students, continues to make significant advances spanning diverse areas in ocean science, technology, and engineering research. In 1997, 42 principal investigators led 147 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, and physical-biological interactions. In the technology category, AOP&E staff are developing a wide variety of ocean sensors, data acquisition systems, 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.

Two new Assistant Scientists joined the department. They are Hanumant Singh, who develops data synthesis methods for underwater vehicles, and Jim Preisig, who is developing physics-based signal processing algorithms for oceanographic applications such as acoustic communication. Both are MIT/WHOI Joint Program graduates who have just completed WHOI Postdoctoral Investigator appointments.

Cheryl Ann Butman and Jim Lynch were promoted to the position of Senior Scientist, and Bob Ballard retired after a 30-year association with the institution and was appointed Scientist Emeritus. Also, Ken Prada and Stan Rosenblad retired after their respective 31 and 24 years of service.

Several AOP&E staff were formally recognized through various honors and awards. Bob Ballard received the Excellence in Geophysical Education Award of the American Geophysical Union, and Cheryl Ann Butman was awarded the Pew Fellowship for Conservation and the Environment. Chris von Alt received a WHOI Senior Technical Staff Award. Larry Flick and Ann Henry, along with the other Center and Department Administrators, received the WHOI Penzance Award for 1997.

—*Timothy K. Stanton, Department Chair*

A New Moored Instrument for Global Ocean Monitoring

***John M. Toole**, Senior Scientist,*
Physical Oceanography Department
***Daniel E. Frye**, Senior Research Specialist,*
Applied Ocean Physics & Engineering Department
***Kenneth W. Doherty**, Senior Engineer,*
Applied Ocean Physics & Engineering Department

To unravel the ocean's role in global climate change, oceanographers desperately need long-term observations of ocean water properties and circulation patterns. Some of the few, treasured sources of such information are the time-series observations once obtained from a network of ocean weather stations established after World War II in the North Atlantic and Pacific Oceans to both guide transocean-voyaging aircraft and make soundings in the atmosphere and ocean. This array was augmented in 1954 by an oceanography-only station offshore from Bermuda, and more recently by stations offshore from Hawaii (1988) and the Canary Islands (1994). The oceanographic and meteorological observations obtained from these long-term stations have been used extensively.

Tom Kleindinst

Steve Liberatore and Terry Hammar conduct a final check of a Moored Profiler off the WHOI pier prior to its deployment for the Turbulence and Waves above Irregular Sloping Topography (TWIST) experiment.

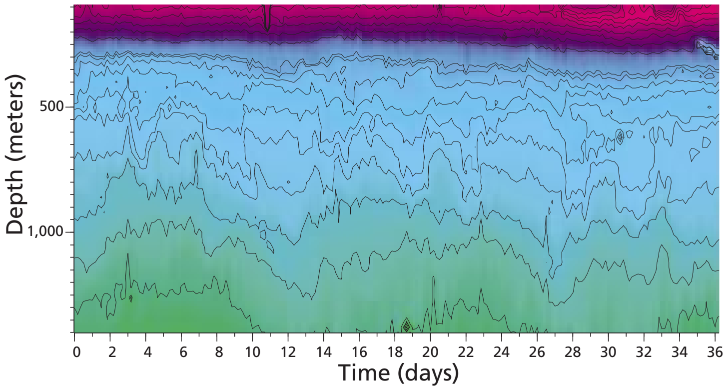
Much of the pioneering research on the ocean's surface mixed layer was based on data collected at a weather station in the Gulf of Alaska. Remarkable, decadal, time scale variability of deep convection and water mass formation were documented by the observations from the Norwegian Sea, Labrador Sea, and the Bermuda stations. By the 1970s, jet aircraft had grown less dependent on surface beacons, satellites were returning global weather data, and the expensive ship-based permanent observing programs were largely abandoned. Long-term, continuous time-series data are currently being collected at only six sites worldwide, often at infrequent and irregular intervals.

With support from the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration, we are working to fill this critical data gap through development of a new instrument called the Moored Profiler (MP). Rather than being fixed at a specific depth, the MP uses a small electric motor with a traction drive to move vertically along a mooring wire at approximately 1 foot per second. Oceanographic sensors fitted to the vehicle are thus profiled through the ocean repeatedly, returning data from one site at high vertical resolution, akin to what was once obtained from the ocean weather ships. Beyond improved resolution, the advantages of this approach over the conventional use of moorings with many discrete sensors at fixed depths include lower cost (only one set of expensive sensors and recording electronics is required) and simplified calibration (intercalibration of multiple, unattended discrete sensors is, at best, difficult).

A key instrument design problem concerned how to keep the energy requirements sufficiently low to allow hundreds of vertical profiles over the course of a year or longer. The instrument we arrived at consists of two 12-inch glass spheres to house the low-power controller and batteries, an electric motor in its own pressure housing, and a set of oceanographic sensors (manufactured by Falmouth Scientific, Inc.) all enclosed in a streamlined fiberglass cowling to minimize hydrodynamic drag. Power from the motor is transferred to the drive wheel through a magnetic coupler, thereby eliminating shaft seal friction. The entire device is ballasted to be neutrally buoyant to minimize the work required to move vertically. Extensive use of glass and plastic (which are far more compressible than metal) helps to limit the buoyancy changes experienced as the device travels between the top and bottom of the ocean. The present system is capable of one million meters of vertical excursion using a 16-pound lithium battery pack. A new lower- power sensor suite combined with a lower-drag instrument shape now in development may extend the range to two million meters. Thus, data from daily excursions from the surface to 5,000 meters could be collected for a full year, or weekly excursions could be maintained for five years or more.

We have tested instrument prototypes offshore from Bermuda and in the Labrador Sea. Most recently, a 37-day deployment was completed in 1,500 meters of water off the New England shelf with the instrument completing more than 500 profiles totalling about 700 kilometers of vertical distance. Temperature, salinity, and horizontal velocity information was collected every 2 meters between 100 and 1,400 meters depth with a new profile initiated approximately every 100 minutes. These data are presently being analyzed to investigate the nature of internal waves over the continental slope. A follow-on research program utilizing three profilers is scheduled for early summer 1998 and longer-term trials are underway near Bermuda.

Our present inventory of five prototype Moored Profilers constitutes a nascent shared-use Institution facility. Plans are underway to greatly increase the instrument inventory of the facility and to supply profilers to the research community. As part of this process, the technology is being transferred to a commercial vendor, McLane Research, Inc. of Falmouth, MA. A long-term goal is to permanently instrument sites around the globe with a combination of Moored Profilers and newly developed drifting and/or self-maneuvering profiling floats to gradually overcome today's lack of long records of ocean variability.



Variability of ocean salinity observed by a Moored Profiler during a test deployment south of Woods Hole. Colors correspond to different salinity values (practical salinity scale) with magenta denoting values greater than 36 and green those less than 34.9.

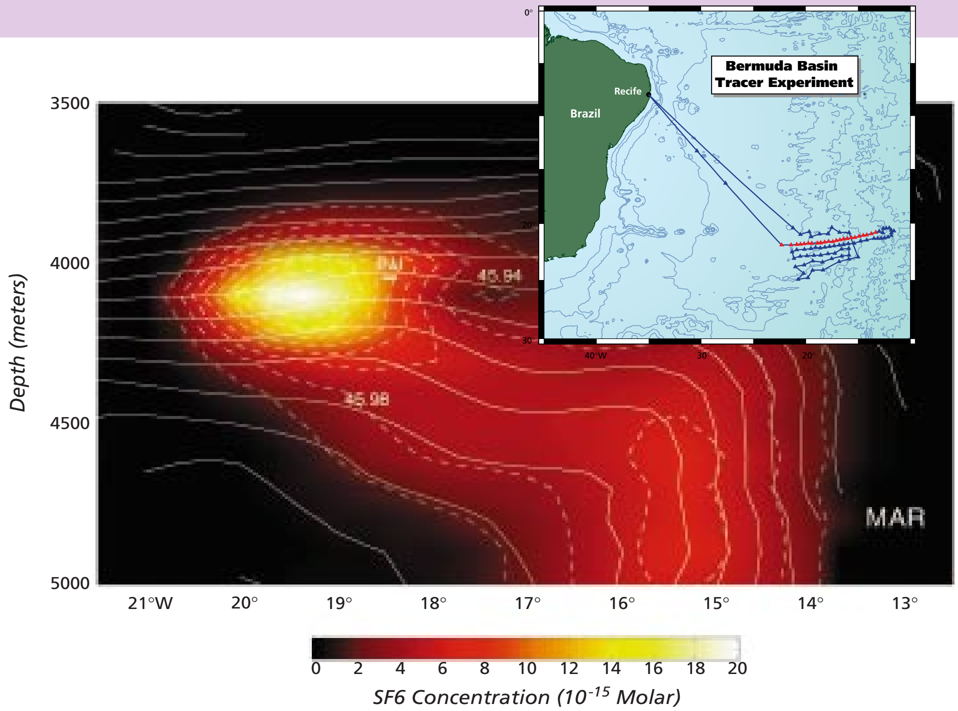
Tracers Delineate Abyssal Mixing in the Brazil Basin

***James R. Ledwell**, Associate Scientist*

One piece of the world ocean circulation puzzle is heating of the very coldest, densest water that forms around Antarctica, plunges to the abyss, and spreads northward to renew the bottom waters of the Atlantic, Indian, and Pacific Oceans. A few million cubic meters per second of this dense water flows north through a narrow gap in the Rio Grande Rise, which forms the southern rim of the Brazil Basin at 30°S. Surprisingly, less dense water leaves the basin over the rise bounding the basin at the equator and through the fracture zones that cut through the Mid-Atlantic Ridge to the east. The puzzle is how this water becomes less dense, and the same question can be posed for all of the world ocean's abyssal water.

Geothermal heating from the crust comes to mind, but measurements show that it is 100 times too feeble. The water's density must be decreased by turbulent mixing with lighter overlying water. However, the density stratification of the ocean severely limits mixing. In fact, turbulence measurements have suggested that there is not enough mixing to lighten the abyssal water. Hence the puzzle, and our project to explore the abyssal Brazil Basin for turbulence and mixing. Collaborators in this work include John Toole, Kurt Polzin, Ray Schmitt, and Breck Owens of the WHOI Physical Oceanography Department.

We have found that turbulence levels are indeed far too low for mixing to lighten the water in the western half of the basin, where the bottom is relatively smooth and the tidal currents weak. However, the turbulence levels are much higher in the eastern half of the basin, where tidal flows are amplified by the presence of the Mid-Atlantic Ridge and where the bottom is exceedingly rough. Turbulence increases strongly toward the bottom and toward the Mid-Atlantic Ridge, although it is relatively high to within a few hundred meters of the ocean surface in this region. It seems that energy for mixing is



Tracer distribution in the Martin Vaz Fracture Zone 14 months after release. The cruise track and location of the section (red line) are shown in the inset. The bottom depth is greater than 5,000 meters in the western (left) half of the section, and is near the end of the contour lines in the eastern half. The small bar marked 'INJ' shows the initial patch. The cloud just to the west of this site indicates strong enough mixing to balance the heat budget of the abyssal basin if it prevailed over the whole basin. However, the mixing is known to be much weaker over the western half of the basin. The deep cloud to the east suggests that the mixing increases strongly enough toward the rough bottom to make up for the weak mixing in the west. The density surfaces, indicated by solid lines, bend downward near the tops of the ridges that bound the fracture zone. The mid Atlantic Ridge (MAR) rises to less than 4,000 meters depth at the eastern edge of the section.

carried upward by internal waves generated by the tidal motions over the rough bottom.

We are using a tracer to measure the actual rate of mixing associated with the turbulence in one important part of the basin. Early in 1996 a little over 100 kilograms of sulfur hexafluoride* were carefully released on a density surface at 4,000 meters depth, about 500 meters above the rough topography in the eastern part of the basin. Neutrally buoyant floats were released with the tracer for tracking purposes and to study the lateral stirring motions of the water. Fourteen months later, in the spring of 1997, the tracer patch was found to have spread dramatically, showing even higher levels of mixing than inferred from the turbulence measurements. The tracer that drifted to the west, away from the Mid-Atlantic Ridge but still over rough topography, experienced enough mixing to lighten the abyssal water at the required rate—but only if the mixing were that high over the whole basin. Tracer that stayed close to the release point, or moved moved east, on the other hand, was found to have mixed strongly into dense water, some of it having travelled hundreds of kilometers along the fracture zones that emanate from the Ridge. This part of the distribution implies extremely high mixing rates within a few hundred meters of the bottom, probably high enough to make up for the quiet prevailing over the western part of the basin.

Tides and rough topography are widespread in the ocean, and tend to occur together, so perhaps we have found the mechanism that can lighten the very densest water in the ocean. That would not mean the abyssal circulation is completely understood; instead, new questions have been raised. Concentration of the mixing near the bottom and in limited parts of the ocean has intriguing ocean circulation consequences, which are being addressed with renewed interest, partly as a result of our work. Also, the mixing mechanism we are finding plays less of a role higher in the water column, farther from the rough topography. There, the lightening of dense waters formed at high latitudes is also somewhat of a puzzle, and may require a different mechanism for its solution, or perhaps a subtle blend of mechanisms, including the one we have found acting in the abyss.

*Sulfur hexafluoride is virtually inert in the environment and harmless to marine life. It is a minor greenhouse gas, but the amount used for the experiment is trivial compared with the present atmospheric burden. The main reason for restraint in its use as a tracer is consideration of the potential for future oceanographic experiments.

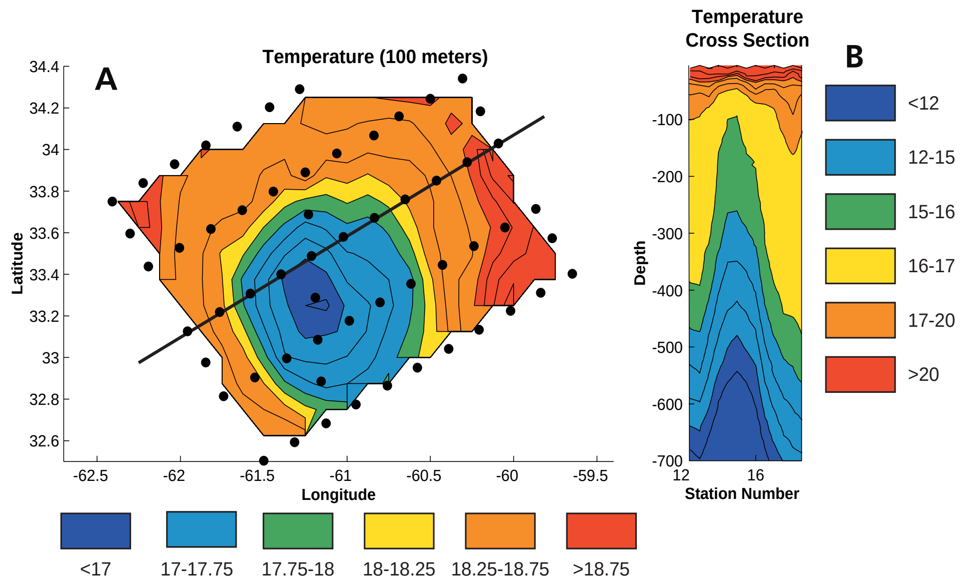
Turbulent "Storms" in the Sea Impact Biological Productivity

***Dennis McGillicuddy**, Assistant Scientist*

Just as atmospheric weather patterns profoundly affect the plants and animals living on the surface of the earth, the ocean's environmental fluctuations also exert fundamental control over the organisms living within it. The currents, fronts, and eddies that comprise the "internal weather of the sea" are highly energetic features of ocean circulation, with spatial extents on the order of tens to hundreds of kilometers and durations of weeks to months. Their space scales are thus smaller and their time scales longer than their counterparts in atmospheric weather, but the dynamics of the two systems are in many ways analogous.

New evidence suggests that the internal weather of the sea could play a vital role in providing nutrients to the microscopic plants called phytoplankton that inhabit surface waters. In the process of photosynthesis, these organisms combine light energy from the sun and nutrients delivered from the deep sea to manufacture organic material. This primary production by phytoplankton forms the basis of the marine food chain, and is therefore fundamentally important to oceanic ecosystems. Furthermore, the chemical transformations involved in photosynthesis use carbon dioxide and produce oxygen in large enough quantities that they may have considerable implications in terms of the earth's climate.

It has long been recognized that the biological productivity of the open ocean far surpasses that which can be sustained by the well-known mechanisms of nutrient supply. Recent results from several different investi-



A, at left, shows temperature at 100 meters derived from shipboard measurements in a cold eddy taken July 7–13, 1997, and B is a temperature cross-section along the solid line indicated in A.

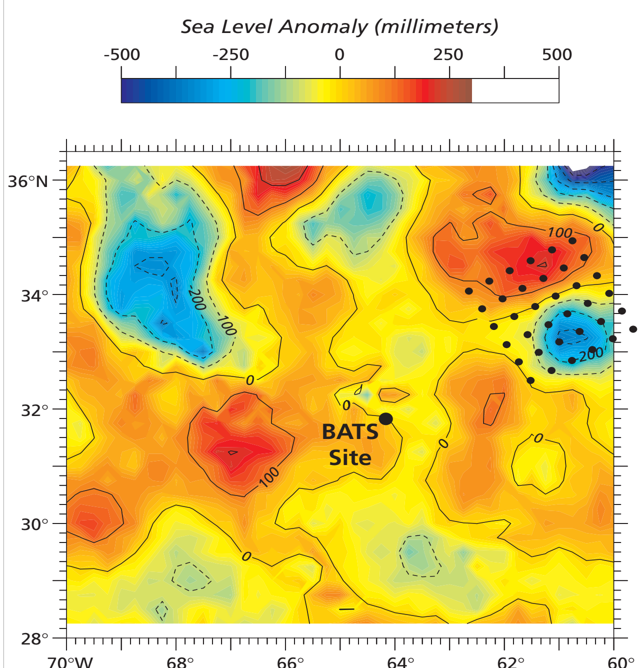
gations now suggest that turbulent storms in the interior of the ocean transport huge quantities of nutrients from the deep sea into the well-lit surface layers. Intense upwelling induced by these episodic events appears to fuel massive profusions of life in localized areas that would otherwise be biologically barren.

The very nature of these bursts in productivity makes them difficult to study. Because they are so intermittent, these features largely escape detection by traditional oceanographic sampling techniques. In order to observe them directly, measurement systems need to be deployed *in the right place, at the right time*. Fortunately, new methods of synthesizing satellite data and computer models permit scientists to locate these areas in real time, making it possible to guide research vessels directly to where such events are in progress.

Such an expedition was conducted in the summer of 1997 in collaboration with scientists from the Bermuda Biological Station for Research (BBSR), the University of California, Santa Barbara, and the University of Colorado. Data from the TOPEX and ERS-2 satellite altimeters were used to map oceanographic conditions in the vicinity of the Bermuda Atlantic Time-series Study (BATS) site. These instruments can measure very subtle (tens of centimeters) changes in sea level height associated with the internal weather of the sea. An analysis constructed just prior to the departure of R/V *Weatherbird* (BBSR) on July 1 (figure at left) showed the area around the BATS site to be relatively quiescent. However, there was an intense interaction occurring between a warm and a cold eddy about a 24 hour steam to the northeast of Bermuda. A decision was taken to occupy a grid covering most of the cold feature, the region of interaction, and about half the warm eddy.

During survey operations, data were transmitted from R/V *Weatherbird* to Woods Hole via Inmarsat so the entire research team had full access to the hydrographic measurements less than one hour after the completion of each station. This facilitated real-time analysis of the evolving eddy pair as survey data flowed in from the ship and new satellite passes became available. This turned out to be very useful for optimizing sampling operations as conditions changed. Toward the end of the cruise, weather conditions began to deteriorate, forcing us to abandon the final leg of sampling in the warm eddy. However, we turned this into an opportunity to sample the center of the cold eddy as the ship steamed south to avoid the weather. The combination of real-time satellite data and shipboard measurements allowed us to pinpoint the exact center of the feature, where a final station was occupied before the steam back to Bermuda.

The figure above shows data taken during a complete survey of the cold feature accomplished earlier in the cruise. A vertical cross-section across the center of the eddy reveals the substantial displacement of temperature surfaces associated with the feature. Water parcels from as deep as 350 meters appear to have been in contact with the base of the biologically active surface layer (at approximately 100 meters). The effects of this disturbance on the plankton ecosystem were dramatic. Nutrient concentration at 120 meters in the core of the eddy was increased more than tenfold, and plankton biomass was enhanced in the overlying waters. Although the analysis of these data sets is still in its very early stages, we have high hopes that they will shed light on some of the impacts of eddy dynamics on biological and chemical processes in the open ocean.



Satellite-derived map of sea surface height for July 1, 1997. BATS is the Bermuda Atlantic Time-series Study site. Red areas indicate bulges in the sea surface associated with warm eddies, while blue areas represent sea surface depressions due to cold features. Small black dots mark shipboard sampling locations.

The Biology Department is a diverse group of researchers with interests in a wide range of organisms, from viruses and bacteria through whales and birds. We work at sea, in the laboratory, and sitting in front of computers, using methods and approaches ranging from molecular biology to acoustic and video sampling to behavioral studies and mathematical modeling. In 1997 our scientific staff numbered 24, along with three active retired scientists, 10 postdoctoral scholars or investigators, 12 technical staff, 37 Joint Program students, and 25 other support staff. Our scientists pursued nearly 150 separate research projects during the year, and published over 50 scientific papers and four books.

Areas of particular research strength include the ecology and physiology of bacteria and protozoa; bio-optical studies of phytoplankton physiology; advanced optical and acoustic approaches to the study of zooplankton distribution and behavior; distribution and ecology of invertebrate larvae; analysis and modeling of life history; population dynamics and physical-biological interactions; toxicological and molecular research concerning pollution effects on marine organisms; and acoustical, anatomical, and behavioral studies of whales and dolphins.

It remains a challenge to secure adequate Federal funding for research in oceanography, but our staff are finding increasingly diverse sources of support from government agencies, foundations, private donors, and Institution programs. Last year we submitted a total of 131 proposals to all sources, and received at least partial funding for 44 percent of them. Leadership and participation by our staff in large national and international programs remains strong, including Joint Global Ocean Flux Study research in the Atlantic and southern oceans; Ridge Inter-Disciplinary Global Experiments, InterRIDGE, and Larvae at Ridge Vents programs for hydrothermal vents; the Office of Naval Research University Research Initiative Program in modeling biological-physical interactions; and the US Global Ecosystems Dynamics Northwest Atlantic Program on Georges Bank, which has its headquarters in the WHOI Biology Department. A notable addition in 1997 was establishment of the national Ecology and Oceanography of Harmful Algal Blooms Program, under the leadership of Don Anderson.

Staff changes in 1997 included the departure of Associate Scientist Brian Howes and the retirement of Senior Scientist Joel Goldman. Darlene Ketten joined the staff as an Associate Scientist, adding her expertise in anatomy and hearing to our marine mammals group. We appointed Rebecca Gast, formerly a Postdoctoral Fellow, as a new Assistant Scientist working on ecology and evolution of protozoans, and David Caron was promoted to Senior Scientist in 1997. Assistant Scientist Heidi Sosik was honored with an ONR Young Investigator Award, our second in two years.

—Laurence P. Madin, Department Chair

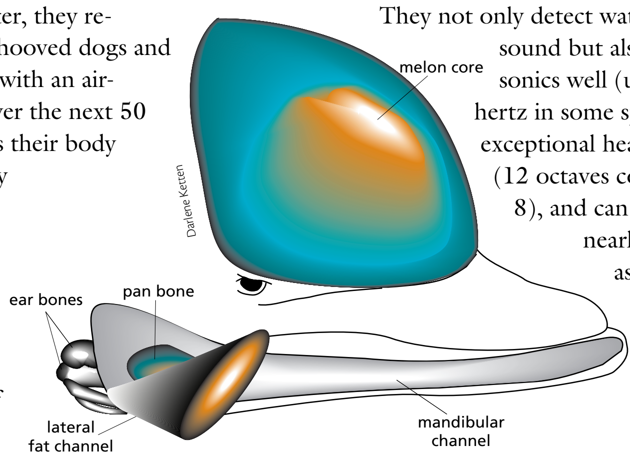
New Laboratory Aids Modeling of Dolphin Sonar Systems

Darlene R. Ketten, *Associate Scientist*

Despite three decades of research devoted to understanding how dolphins generate and analyze sound, scientists have been unable to design a system that replicates a dolphin's sonar abilities. My research seeks to improve our knowledge of dolphin sonar by explaining the biological mechanisms involved in dolphin sound processing. In part, this requires understanding how the highly specialized head and ear anatomy of cetaceans (whales and dolphins) is related to underwater hearing. To accomplish this entails, literally, taking apart whale heads. To do this, old-fashioned dissection is now being coupled with new biomedical imaging techniques that produce computerized models for a unique, three-dimensional view of how dolphin and whale hearing works.

Cetacean ears are unique. They are larger, denser, and more complex than any other mammalian ear known. All whales and dolphins evolved from land-based carnivores called condylarths. When condylarths first entered the water, they resembled large, hooved dogs and were equipped with an air-adapted ear. Over the next 50 million years, as their body shapes gradually evolved to preserve heat and move efficiently in the comparatively dense, cold environment of the oceans, their ears changed in tandem, becoming progressively better adapted to the substantially different physical parameters of sound in water versus air.

Today, cetaceans have the only mammalian auditory system completely adapted to underwater hearing, and echolocating dolphins appear to have particularly acute ears. They not only detect water-borne sound but also hear ultrasonics well (up to 200 kilohertz in some species), have exceptional hearing ranges (12 octaves compared to our 8), and can localize sounds nearly twice as well as the average human. Like their nocturnal land cousins, the bats, dolphins are true echolocators that "image" their environment with sound. To be an effective

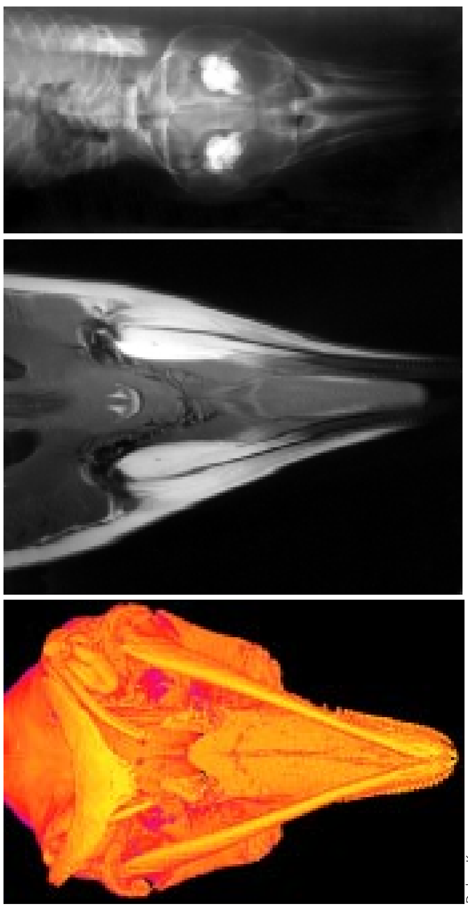


This schematic shows three key adaptations for dolphin echolocation and hearing. Underwater sounds are transmitted and captured by specialized fats in the dolphin head that have acoustic impedances equal to seawater. Outgoing ultrasonic pulses are projected and focused by the bulbous fatty melon of the dolphin "forehead," while returning ultrasonic echoes and lower frequency communication signals are captured and channeled to the ear by paired fatty lobes in (mandibular channel) and around (lateral channel) the lower jaw.

echolocator, an animal must be able to both generate a discrete, directional signal and rapidly analyze changes in the acoustic features of echoes created by objects in the sound field.

We have a fairly good idea of bats' echolocation mechanisms, but much of the dolphin's ability remains a mystery. Key issues are:

- How, given no outer ear or patent ear canal, does sound enter the dolphin head?
- How, given rapid sound speeds in water, do dolphins localize sounds?
- How do they generate and detect extraordinarily high frequencies?



Darlene Ketten

Bright white ear bones are shown surrounding the spiral inner ear of a spinner dolphin in a plain film X-ray (top panel). An MRI image of this head in the same plane (middle panel) reverses the densities and shows the ear bones as black spaces but reveals bright bands of jaw fats leading to the inner ear. A 3-D reconstruction from CT scans of a dolphin head (bottom panel, ventral view) shows the actual, undisturbed placement of the ear behind the jaw. Superimposing these images shows the crucial relationship of the specialized acoustic fats to the ear.

Sean Todd

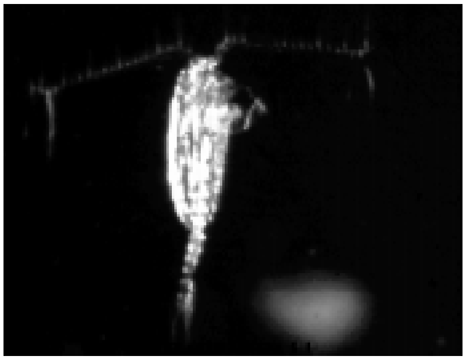
Jon Lien (St. John's Memorial University, Newfoundland) and Darlene Ketten conduct a postmortem exam of a stranded, Newfoundland humpback whale. The whale is lying on its back. The lower jaws and tongue were removed to get access to the ears and brain. Ketten is standing on the upper palate. The ears are the two white bones in front of her knees. Each ear weighs approximately one kilogram and is about the size of an adult human head.

Previously, dolphin sonar was investigated primarily through behavioral tests and electrical models that tried to mimic their performance. Recently, funding from the Office of Naval Research, the Seaver Institute, and the Mellon Foundation, in combination with the construction of a specially designed marine mammal dissection laboratory at WHOI, has allowed us to probe dolphin echolocation at the source by analyzing dolphin hearing from a macro (whole head) to micro (inner ear) structural perspective.

For micro-level data, whole ears are extracted during post-mortem exams, or necropsies, of stranded dolphins and processed to obtain thin sections of the inner ear that are examined with light and electron microscopy. These analyses produced the first key to dolphin ultrasonic abilities. Ultrasonic hearing in dolphins is somewhat surprising because in general, the larger the animal, the lower its hearing range. Based on size alone, the average bottlenosed dolphin should not be able to hear past 20 kilohertz, but they routinely hear well up to 160 kilohertz. Inner ear histologies revealed that dolphins have specialized membrane supports that increase the inner ear's stiffness range. This accounts not only for their ability to perceive ultra-high frequencies despite their size but also explains how they achieve exceptional hearing ranges.

These data are now being combined with sectional data on a much larger scale. Entire animals are currently being "dissected" using experimental ultra-high resolution computerized tomography, or UHR-CT and MRI scanning. In the last year, 30 marine mammals from 11 species were scanned. Most were post-mortem strandings, but a few live animals were also scanned to assist in their medical treatment. These new biomedical imaging techniques allow us to digitally dissect each animal without disturbing structural relationships that are imperative for understanding its head geometry. Even more important, because CT and MRI images are based on X-ray attenuations and fluid content, they also provide direct measures of tissue characteristics that correlate with density and acoustic impedances. Consequently, these data can be used to produce three-dimensional computerized reconstructions of entire heads that are graphic maps of any selected tissue grouping, such as the ear versus brain versus fats, etc. Preliminary data from these studies suggest dolphin localization abilities are related to the placement of their ears outside their skull. They also show that dolphins have multiple specialized fat channels attached to each ear that may act as bi-directional sound conduits.

This combined approach of three-dimensional anatomic, morphometric, and physical modeling of the dolphin ear has provided the first comprehensive anatomical model for the dolphin sonar receptor system. In the next phase, we hope to use these data to develop computerized finite element models that simulate acoustic responses of dolphin heads and ears to a range of acoustic stimuli, and ultimately to apply these techniques to a broader range of marine mammal auditory models to estimate hearing for rare species, such as the sperm whale and blue whale, and provide a means of estimating noise effects on marine mammal ears to assist in the development of responsible policies for use of sound produced by humans.



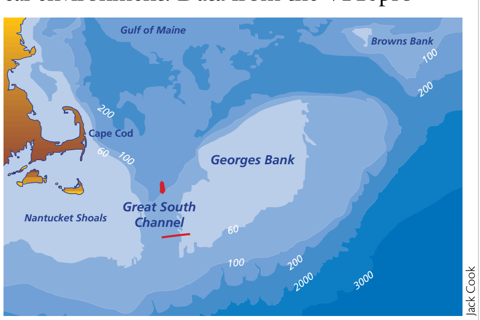
Video plankton recorder image of the copepod *Calanus finmarchicus* on Georges Bank. The animal is 3 millimeters long, head to tail.

Automated Real-Time Plankton Identification

Cabell S. Davis, *Associate Scientist*
Scott M. Gallager, *Associate Scientist*

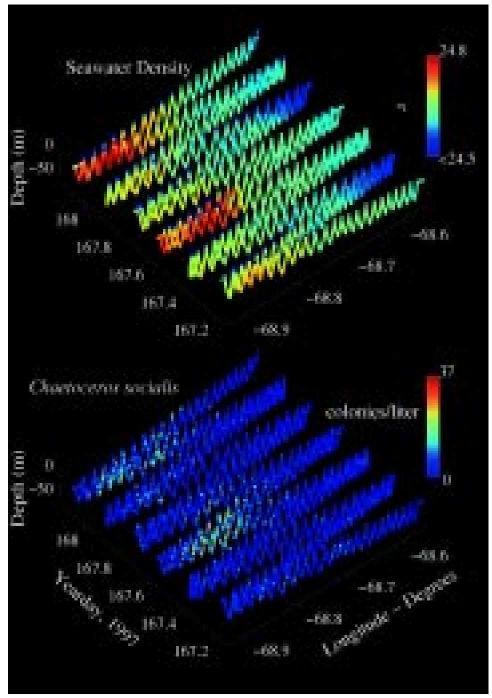
The vast bulk of living matter in the ocean is contained within the plankton (small plants, animals, and microbes that drift passively with the ocean currents). Most species of marine animals are planktonic during at least a portion of their life cycles. Thus the plankton includes familiar groups such as fish, crabs, shellfish, and starfish (all of which have planktonic larvae) as well as less familiar forms that remain planktonic their entire lives. The latter include the copepods, which are arguably the most numerous animals on Earth and are a critical link in the ocean food chain between primary producers and higher levels such as fish.

For the past four years, we have been using the Video Plankton Recorder (VPR), a towed underwater microscope, to measure the distributional patterns and behaviors of planktonic organisms in relation to the physical environment. Data from the VPR provides an understanding of the mechanisms that control plankton abundance in the ocean and how it may affect and be affected by perturbations such as changes in fish stocks, pollution levels, and global climate.



Map of study area showing locations of sampling sites (red) in the Gulf of Maine and the Great South Channel.

Traditional methods for measuring plankton distributions involve use of bottle and net collections that destroy fragile forms and require time-consuming laboratory analyses. Data from even a single plankton survey can take months or years to obtain. Sampling plankton using video allows quantification of delicate forms as well as providing an opportunity for automated analysis.

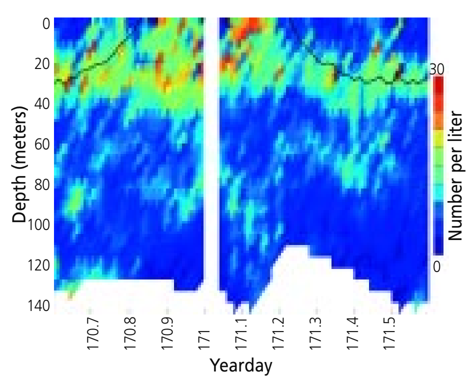


Three-dimensional dot plots of seawater density and *Chaetoceros socialis* abundance showing the time evolution of the tow. A patch of colder, saltier water containing *C. socialis* is seen to enter the western end of the transect during the end of each 12 hour tidal cycle.

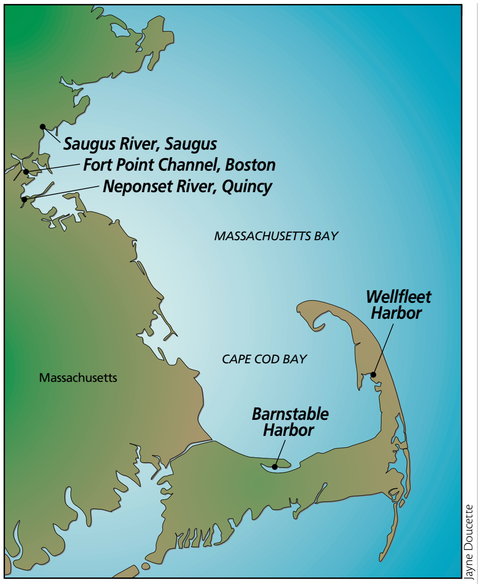
In 1997, with funding from the Office of Naval Research, the VPR group successfully completed development of a real-time automated system for analyzing the VPR video. The newly completed system was used during an R/V *Endeavor* (University of Rhode Island) cruise in June as part of the Global Ocean Ecosystem Dynamics (GLOBEC) Georges Bank study, which is funded by the National Science Foundation.

This VPR cruise represented a milestone in plankton ecology by allowing scientists, for the first time, to visualize distributional patterns of plankton species automatically in real time. The figures above and right show examples of data obtained with the system at the two study sites identified in the figure at left. Above, the distribution of the colonial diatom *Chaetoceros socialis* was measured over two tidal cycles along a 40 kilometer east/west transect in the Great South Channel region of Georges Bank. During the northward excursion of the tide, a large patch of these algae was observed to enter the western end of the transect in a high-density water mass. North of this region, in the Gulf of Maine, the copepod *Calanus finmarchicus* was observed to migrate vertically from within the pycnocline (zone of rapid density change with depth, usually due to changes in temperature and salinity) during the day, spread throughout the upper mixed layer at night, and then retreat back to the pycnocline the following day (see figure below).

We have proposed using the VPR system on Georges Bank as part of GLOBEC in 1999 to provide data in real time to a coupled biological/physical model in order to quantify flux of plankton across the boundaries of the bank. The new capability of real time visualization of plankton species distributions will enable biological oceanographers to adapt their sampling strategies on board ship, thus improving our understanding of the processes controlling plankton patterns in a dynamical ocean environment.



Distribution of *Calanus finmarchicus* showing its diel migration behavior. The animals remain at a depth of about 20 meters during the day, spread throughout the upper water column at night, and retreat back to 20 meters the next day.



Clams were sampled for contaminant effects at five sites.

Contaminant Effects in Soft Shell Clams

Judith E. McDowell, Senior Scientist

Organic compounds from society's wastes—such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs)—are highly resistant to degradation in the marine environment. Once deposited in marine sediments, these organic contaminants remain available for uptake by marine organisms for long periods and may, then, affect the health of marine populations or be passed up the food chain to humans.

PAH contamination of coastal ecosystems is derived from sources that are both pyrogenic (for example, burning of fossil fuels) and petrogenic (such as oil spills and other sources of petroleum contamination). These compounds or their metabolites may accumulate to high levels in animal tissues and interfere with normal metabolic processes that affect growth, development, and reproduction. Sediments and living organisms from Boston Harbor show high levels of a variety of organic contaminants including PAHs, chlorinated pesticides, and PCBs. In fact, Boston Harbor blue mussel tissues exhibiting high PAH concentrations are among the most contaminated US coastline samples analyzed in the National Oceanic and Atmospheric Administration's National Status and Trends Program, a nationwide monitoring program designed to examine temporal and spatial gradients of contaminants in coastal environments.

Though there have been improvements in Boston Harbor ecosystem water quality as a result of recent wastewater treatment system upgrades and reduction in point source contamination, harbor sediments will continue to be a major source of contaminants to Massachusetts Bay. Recent studies of tumors and other disorders in bottom-dwelling fish and shellfish from contaminated coastal areas suggest a possible link between levels of selected organic contaminants and the increased incidence of histopathological conditions (changes in tissues caused by disease).

In a collaborative study with Damian Shea of North Carolina State University, we examined the effects of organic contaminants on population processes in the soft-shell clam *Mya arenaria* collected along a gradient of PAH contamination in Boston Harbor and Massachusetts and Cape Cod Bays. As previous geochemical studies indicate, not all of the contaminants within the sediments are available for uptake by such species as the soft shell clam. Contaminants were detected in clam tissues and sediments from all sites, but uptake of specific compounds varied at different sites. As the table below illustrates, highly contaminated sediment samples from three urban stations have relatively similar concentrations of contaminants in clam tissues, whereas sediment contamination differs by as much as 50-fold.

Clam populations at the three most contaminated sites (Fort Point Channel and Saugus and Neponset Rivers) exhibited similar patterns that indicate limited energy available for reproduction: lipid (fatty compound) accumulation reduction in the digestive gland-gonad complex and spawning limited to a single midsummer event (more commonly spawning would occur over a prolonged period). Highest levels of reproductive output were observed among clam populations from uncontaminated sites (Barnstable and Wellfleet Harbors), and spawning at these sites occurred from late spring to early fall. High prevalence of a gonadal inflammatory disease and a leukemic-type disease of the circulatory system was observed among clam populations from the three heavily contaminated sites, especially at the most contaminated site where levels of the leukemic disease reached 100 percent during winter sampling.

The results of this study confirm and extend the observations of several other investigations conducted in the Massachusetts Bays ecosystem with the basic findings being:

- marine animals readily accumulate organic contaminants, yet processes limiting their availability for uptake, especially at heavily contaminated sites, are not yet explained;
- marine populations exhibit alterations in reproduction and energetic processes and increased prevalence of disease when they live in contaminated habitats, but the interaction of contaminants with natural disease defense mechanisms are not well understood; and
- shellfish resources at several urban sites in Massachusetts Bay show elevated concentrations of organic contaminants, especially PAHs, which must be considered in any management plan that involves harvesting or remediating these contaminated stocks.

The information generated in this study can provide the basis for initial assessment of ecological and human health risks associated with PAH contamination in harvestable resources and habitats. This is important not only for coastal ecosystems in Massachusetts Bay but coastal ecosystems throughout the world.

Site	Total PAH			Total PCB			Total DDT		
Barnstable Harbor	352	300	271	0.5	11.5	5.3	0.2	9.1	4.4
Wellfleet Harbor	102	367	319	<0.1	14.7	6.5	0.2	0.4	0.4
Saugus River	18,342	5,110	4,600	12.8	91.1	56.9	5.1	20.6	21.1
Neponset River	1,450	1,900	1,700	5.4	130.5	81.8	2.0	14.4	18.9
Fort Point Channel	66,121	7,370	7,320	34.8	56.7	39.1	26.8	14.4	18.5

Color Key:
Sediment Contaminant Concentrations in Nanograms Per Gram (ng/g) Dry Weight
Pre-Spawning Clams Contaminant Concentrations (ng/g dry weight)
Post-Spawning Clams Contaminant Concentrations (ng/g dry weight)

The addition of three new members during 1997 increased our Resident Scientific Staff to 31 members. This was brought about by the addition of Assistant Scientists Kenneth Simms, Cecily Wolfe and Tracy Gregg. Ken, a former WHOI Postdoctoral Scholar, is a geochemist who uses the uranium decay series as tracers and chronometers of lava extrusion at mid ocean ridges and seafloor volcanoes. Cecily is a former Joint Program student and a seismologist who is using earthquake locations and motion studies to image the structure of the ocean's crust and mantle. Tracy, a former WHOI Postdoctoral Fellow, is a volcanologist who uses the structure and texture of extruded lavas to determine their physical properties and chemistry. Much of her work is based on remote imaging; she is equally at home researching the sea floor and the surfaces of the terrestrial planets. In addition to growth in our scientific staff, our technical staff grew by two and now numbers 23 individuals. Our support staff, now 32 members, grew by four. Although the graduation of several students reduced the size of our graduate enrollment to 28, we maintained a very strong group of nine Postdoctoral Scholars, Fellows and Investigators.

Attesting to the continued intense competition for research funding, the department submitted 163 proposals during 1997, while sixty-one research programs were funded. Forty-eight of these funded programs were new projects. This is typical of our recent success at securing research funding, but at the cost of writing five proposals per investigator. In contrast, the department published 95 peer-reviewed papers in 1997, an average of three per investigator. Our research interests are as diverse as ever. Some important programs include studying the structure and evolution of the oceanic crust and the chemical evolution of the earth's crust and mantle. Others include an expanding research program in coastal geology and sedimentology, monitoring of oceanic particle fluxes and reconstructing the long-term climate history of the earth. Several new programs are beginning that will establish sea floor observatories to monitor basic earth processes including earthquakes. As part of our many research programs members of the department participated in 27 research cruises and field programs, equivalent to a total time at sea of more than one and half years. Senior Scientist Lloyd Keigwin and Associate Scientist Dick Norris were named as Co-chief Scientists of the *JOIDES Resolution* of the Ocean Drilling Program.

Several members of the department received prestigious awards during the past year. Senior Scientist Stan Hart was awarded the 1997 Harry H. Hess Medal of the American Geophysical Union (AGU) for his basic research contributions on the chemistry of the earth. John Hayes, Senior Scientist and Director of the WHOI/NSF National Ocean Science Accelerator Mass Spectrometer, was named co-recipient of the Urey Medal of the European Association for Geochemistry. (The other co-recipient was Geoff Eglinton, who is an Adjunct Scientist in the Department of Marine Chemistry and Geochemistry.) Scientist Emeritus Dick Von Herzen was named the 1998 Maurice Ewing Medal winner by the AGU, which will be presented to Dick at the Fall Meeting of AGU in December 1998. Assistant Scientist Neal Driscoll was awarded an Office of Naval Research Young Investigator Award for his research on the sedimentation and stratigraphy of continental margins.

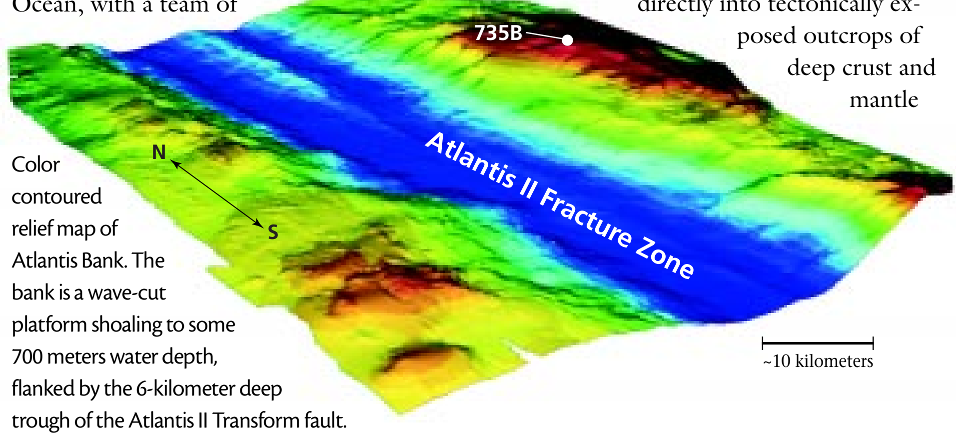
—William B. Curry, Department Chair

1,500 Meters of Ocean Drilling Yields New Knowledge of Ocean Crust

Henry J. B. Dick, *Senior Scientist*

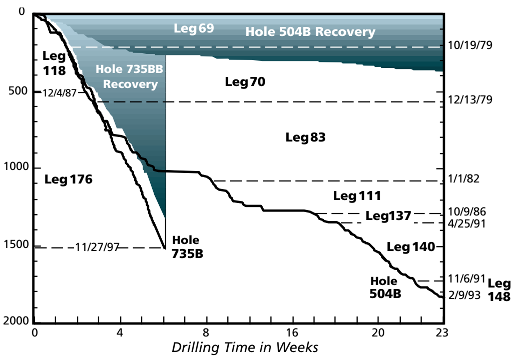
A long sought goal of the ocean sciences community has been to drill the deepest layers of the ocean crust and Earth's mantle beneath. The true nature of the ocean crust, beneath the thin carapace of pillow lavas exposed everywhere along the ocean ridges, has always been a mystery. Although it covers three-fifths of the earth, its composition and architecture have largely been inferred geophysically from seismic layering and from studies of fossil ocean crust found on land (which may be of unusual origin, such as fore-arc and back-arc basins). Various attempts beginning in 1961 to drill the ocean crust proved difficult and frustrating, with low rock recoveries and a shallow penetration.

In 1987, Ocean Drilling Program *JOIDES Resolution* Leg 118 in the Indian Ocean, with a team of WHOI scientists aboard, began by continuing this unfortunate tradition as we tried a new strategy. Numerous attempts to penetrate the rubble and debris on the walls of Atlantis II Fracture Zone in order to drill directly into tectonically exposed outcrops of deep crust and mantle



Color contoured relief map of Atlantis Bank. The bank is a wave-cut platform shoaling to some 700 meters water depth, flanked by the 6-kilometer deep trough of the Atlantis II Transform fault. The crest of the bank is extraordinarily flat, and with the discovery of a fossil fringing reef in spring 1998 (as this 1997 annual report was being prepared) by a US-Canadian-British remotely operated vehicle expedition led by author Henry Dick, Paul Robinson of Dalhousie University, and Chris MacLeod of the University of Wales, is known to represent a wave-cut platform, the sunken remains of an island tectonically uplifted some seven kilometers to sea surface on the wall of the Southwest Indian Ridge rift 11 million years ago.

proved disastrous. Some five weeks into the cruise, the author and James Natland (Scripps Institution of Oceanography) suggested drilling on the top of Atlantis Bank, a 5.5-kilometer-tall seamount flanking the fracture zone, where there might be little rubble. Without a likely alternative, the drill ship steamed off to the bank, where we lowered a TV camera on the end of a drill string and found bare gabbro outcrop (gabbro is crystallized magma that forms the deepest layer of the ocean crust over the earth's mantle). Sixteen days later we had drilled a 500 meter hole into an in-situ section of the lower ocean crust, and, even better, recovered nearly all the rock drilled.



Drilling results for the two most successful hard-rock holes in the ocean crust: Hole 735B penetrated the lower ocean crust formed beneath the Southwest Indian Ridge and Hole 504B the upper ocean crust formed at the Costa Rica Rift in the eastern Pacific. Note that while Hole 504B is deeper, it took nearly four times as long to drill, and only 18 percent of the rock drilled was recovered while some 87 percent of the rock drilled was recovered from Hole 735B.

The scientific results surprised everyone on board. The rocks revealed a complex history of crustal accretion never before envisaged. Instead of the remains of a single large magma chamber, as was thought to exist beneath ocean ridges, there were many small intrusions of primitive olivine gabbro cut by numerous shear zones filled with iron oxide rich ferrogabbros. These rocks were then cut by thick bands of deformed amphibolite formed when seawater percolated down into the deep crust and altered the gabbro. The whole thing reflected a complex interplay of deformation, igneous intrusion, and hydrothermal alteration—which is now widely accepted as the model for formation of the lower ocean crust at slow-spreading ocean ridges.

Was Hole 735B a fluke, simply a lucky sweet spot in the ocean crust for drilling? Or did it represent a new era for ocean drilling? The gabbroic layer of the ocean crust is generally believed to be 4 to 6 kilometers thick—how representative of the lower ocean crust could a 500 meter section be? Despite the excitement about Leg 118 results, the National Science Foundation-funded Ocean Drilling Program was reluctant to commit another $7 million "leg" or voyage to the distant Indian Ocean to find out. However, after some 10 years of arguing the case, a team that included WHOI scientists Ralph Stephen, Greg Hirth, Peter Meyer, Wolfgang Bach, and the author (as co-chief scientist) returned in 1997 to the Indian Ocean aboard *JOIDES Resolution* to deepen Hole 735B.

The results were spectacular. In four weeks of drilling, we deepened the hole to 1,508 meters, making it the second deepest hole ever drilled in the ocean crust, and by far the most successful with 87 percent of the rocks drilled recovered on board the ship. This gave scientists their first meaningful look at a really significant section of intact and in situ lower ocean crust. But rather than being simply a continuation of the features seen in the uppermost 500 meters, the stratigraphy underwent radical changes with depth, becoming less iron-rich, less deformed, and less altered than before. Once again, the models, derived from the upper 500 meters, have to be changed to account for the new observations. Moreover, the results demonstrate that there is no well described and well exposed fossil section of lower ocean crust on land comparable to what was found in Hole 735B. Bits and pieces of shattered, tectonically disrupted ocean crust found on land may match the rocks found in 735B, but none offer the opportunity to fully understand or evaluate crustal evolution and composition.

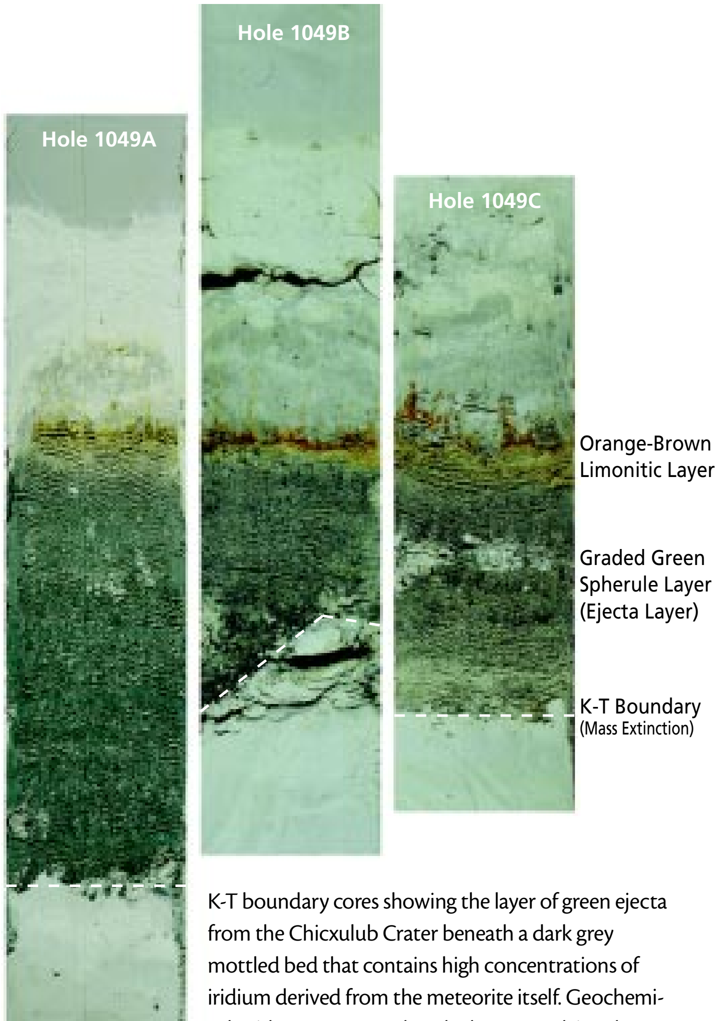
An exact knowledge of the composition of the ocean crust is crucial to understanding planetary evolution and chemical fluxes into and out of the earth. It is now evident that this can only be done by drilling in the oceans, and, as a consequence of the return to 735B, the stakes for ocean drilling have been raised with the demonstration of what is possible when the right site is chosen. Earth scientists have truly entered into the uncharted depths of the earth at Hole 735B, and a great deal more is possible there. Even as we head out on two more expeditions to map the seafloor around Atlantis Bank, including a joint WHOI Japan Marine Science and Technology Center expedition in fall 1998 with the *Shinkai 6500* submersible, we have put a new proposal on the table for a 3-kilometer hole to be drilled there by the year 2000.

Deep Sea Cores Document Historic Extraterrestrial Object Impact

Richard D. Norris, Associate Scientist

Recent ocean drilling results from the Atlantic Ocean (300 miles off northern Florida) provide dramatic support for the long-standing theory that a large extraterrestrial object slammed into Earth about 65 million years ago, at the boundary between the Cretaceous and Tertiary geological time periods, which is known as the "K-T" boundary. This event caused widespread extinctions of perhaps 40 to 70 percent of all species, including the dinosaurs. By drilling multiple holes at Site 1049, Ocean Drilling Program (ODP) Leg 171B recovered three cores containing sedimentary layers that reveal—in beautiful detail—a dramatic story of destruction and biotic upheaval (see photograph on next page).

The lowermost bed contains a 6-to-17-centimeter-thick, graded layer of green globules that closely resemble droplets of glass found around modern impact craters. This "spherule" layer contains bits of "shocked" quartz whose structure has been altered by intense pressures like those associated with impacts and nuclear weapons tests. There are also relatively high concentrations of the platinum-group element iridium, known to be unusually concentrated in meteorites. In addition, we have found bits of rock similar to those known from the



K-T boundary cores showing the layer of green ejecta from the Chicxulub Crater beneath a dark grey mottled bed that contains high concentrations of iridium derived from the meteorite itself. Geochemical evidence suggests that the layers overlying the ejecta bed were deposited during a prolonged "cold snap" during which the first new species appeared after the K-T extinction.

subsurface of the Yucatan Peninsula in Mexico where a large (180-mile-across) impact crater was discovered in the 1970s by oil company drilling. This crater, known as the Chicxulub impact structure, has been dated by radiometric means at 65 million years plus or minus a hundred thousand years—essentially the same date as the K/T mass extinction. Hence, we think we have good evidence that we drilled through the ejecta blanket from the Chicxulub structure.

The new cores are particularly significant because they contain a detailed chronology of when the impact occurred. The ejecta blanket sits precisely at the K/T boundary in the new cores, synchronous with the mass extinction of marine plankton. The fossils immediately above the ejecta bed are both minute and contain few species whereas mud from directly below the ejecta layer contains much larger fossils and a considerably more diverse biota. In previous core studies, it has always been possible to argue that the cores have gaps or that the impact slightly predates the mass extinction. However, studies of the new material make it clear that many of the supposed surviving species were not genuine survivors but had been eroded out of older sediments—perhaps by the enormous waves stirred up by the impact or by the submarine landslides that occurred all over the Gulf of Mexico and the southeastern Atlantic seaboard.

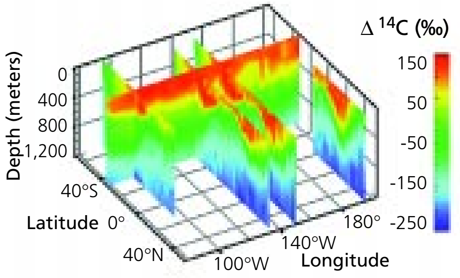
We also have an unusually complete record of how the Earth's biosphere recovered from this monumental insult. Analyses of stable isotopes of oxygen, which record the temperatures of the ancient oceans, suggest that the Earth cooled dramatically in the aftermath of the impact. Many people have speculated that the enormous quantities of dust hurled into the atmosphere by a large impact could produce global cooling for a few months or years. However, the new data suggest that temperatures were depressed in the subtropical Atlantic for perhaps 10 to 15 thousand years before returning to something like preimpact temperatures. It is during this "cold snap" that many of the newly evolved plankton first appeared. Data from Leg 171B make it clear that recovery from the mass extinction in the oceans was prolonged, requiring upwards of ten million years before plankton diversities returned to something approximating preextinction levels.

Good Things Come in Small (...er and Smaller ....) Packages

***Ann P. McNichol**, Research Specialist*

The National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS) Facility provides the oceanographic community with large numbers of high precision radiocarbon (C-14) measurements. The development of accelerator mass spectrometry (AMS) just over 20 years ago revolutionized the analysis of C-14 in natural samples, reducing sample requirements from grams to milligrams and analysis times from weeks to minutes. Radiocarbon data, either alone or coupled with other measurements, can provide powerful information about natural processes, but its low natural abundance, 1 part per trillion in modern samples, makes it difficult to measure. In paleoceanography, radiocarbon serves as a clock that records the timing of events over the past 40 to 50,000 years. In carbon cycling studies, natural levels of radiocarbon can be used to constrain the residence time of carbon in various reservoirs. Additionally, atmospheric weapons testing in the 1950s and 1960s doubled the atmospheric inventory of C-14 and started a decades-long experiment on how quickly the "bomb signal" is being removed from the atmosphere.

Since the inception of NOSAMS in 1989, 60 to 70 percent of our efforts have focused on providing the World Ocean Circulation Experiment (WOCE) Program with up to 2,500 radiocarbon analyses on dissolved inorganic carbon (DIC) a year. We have automated virtually every aspect of preparing and analyzing these samples to improve throughput and repeatability. WOCE scientists are using the results to improve estimates of carbon dioxide (CO_2) exchange rates between ocean and atmosphere under such conditions as upwelling and thermocline ventilation. The figure at the top of page 16 shows a snapshot of the C-14 distribution in the Pacific Ocean. As WOCE winds down to completion in the middle of the year 2000, we are preparing to provide radiocarbon services to a broader



Radiocarbon distribution (expressed as $\Delta^{14}C$) in the Pacific Ocean. High levels at the surface indicate the input of bomb radiocarbon.

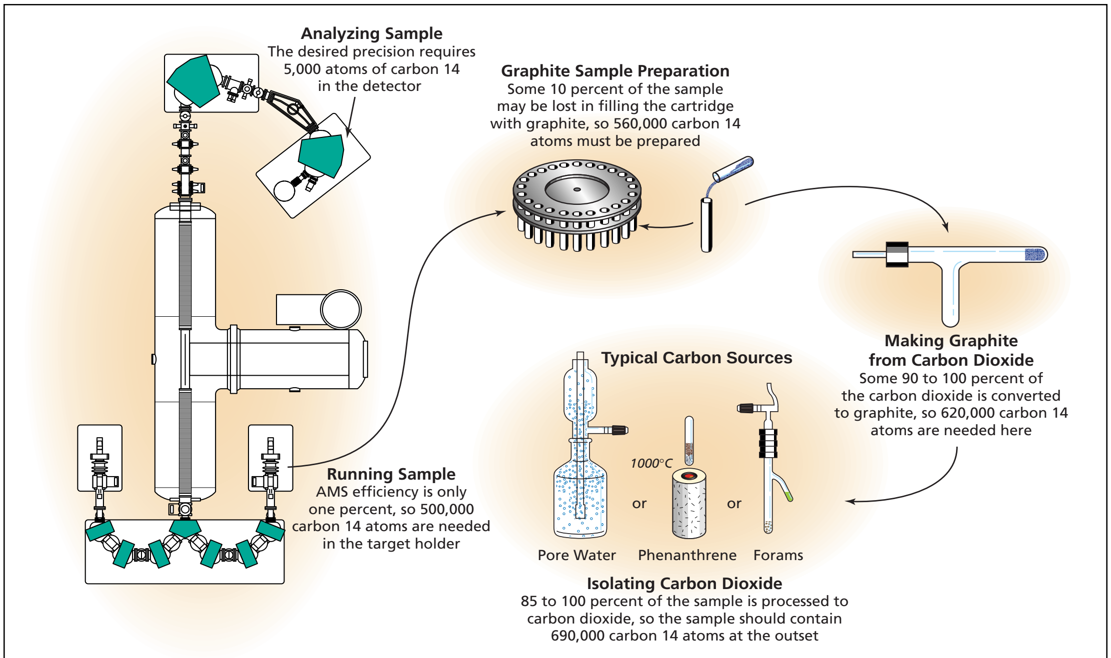
spectrum of the oceanographic community.

The abundance of dissolved inorganic carbon in the ocean, present at concentrations of approximately 2 millimoles per kilogram or above, allows us to optimize our analyses with little regard to sample size limits. While many interesting studies requiring radiocarbon analyses offer abundant sample material, there are also many fascinating issues for which there is little sample material. As just one example, in paleoceanography recent results from Greenland ice cores suggest that the transition from the last glacial maximum (20,000 years ago) to the start of the current interglacial period (8 to 9,000 years ago) was a time of great climatic variability with rapid transitions from cold to warm periods. Global understanding of these events can be gained through studying cores from different geographic regions. Radiocarbon dating on foraminifera isolated from the cores can establish the timing of these events, information critical for defining causal mechanisms. The sites suitable for these studies have high sedimentation rates, but, unfortunately, very low abundance of forams. Any reduction in sample size requirements will increase both the number of sites that can be studied and the confidence in predictions made from these studies.

AMS revolutionized C-14 measurements by "counting" the actual number of C-14 atoms in a sample relative to those in a well-known standard, rather than waiting to count decay events. This allows rapid accumulation of the data needed for a precise result. However, the number of C-14 atoms measured in the AMS is actually much smaller than the amount that is introduced to the accelerator. Just as it is not possible to burn gasoline in an automobile with 100 percent efficiency, our accelerator is not capable of analyzing all the C-14 atoms we put in it. Currently, the best precision we can practically realize from modern samples with no size limitations on our accelerator is 0.3 percent (3 parts per thousand). To offer this precision, we require that our clients provide a sample containing at least 500 micrograms of carbon, that is, 5 milligrams of shell material or 20 milliliters of seawater. For studies that do not require such precision and that are severely carbon-limited, we have developed techniques for analyzing samples containing as little as 20 micrograms of carbon. Samples for these special studies must be chosen judiciously. Sample processing and accelerator efficiency place real constraints on the reliability of C-14 measurements of natural samples. Please see box below for details.

Samples arriving at NOSAMS in raw form, such as foraminifera shells, charcoal pieces, seawater, and bulk sediment, must be "cleaned up" and converted to CO_2 in the Sample Preparation Laboratory. Shell material is acidified, organic matter is burned at high temperature, and seawater is purged with gas; each of these processes can add a small amount of carbon that may contain C-14. The CO_2 gas from each sample is reduced to solid carbon filaments, usually referred to as graphite, in a separate process which also may add some carbon. The samples are then poured into a cartridge and compressed to produce an AMS target. Finally, in the accelerator itself, the carbon is converted to ions that are accelerated through magnetic fields to isolate C-14.

Our techniques work well for these small samples, but we are still trying to improve them. All procedures for handling these small samples external to the accelerator are currently manual, but we intend to streamline and automate them as much as possible.



To understand the limits sample processing and Accelerator Mass Spectrometer analysis place on radiocarbon studies, it is useful to walk a sample backwards from the AMS detector to the raw material required for the analysis. In this example, we assume that we are analyzing samples in a core deposited over a 12,000 year period, and we need to know the measured ages to within 500 years. Thus, the sample we prepare must have at least 560,000 C-14 atoms in it. How much raw material does this require? Because the decay of C-14 over time reduces the amount of C-14 in a sample, the answer will vary as much as tenfold depending on whether the sample is from the top or bottom of the core.

Jack Cook

At the end of 1997, the Department of Marine Chemistry and Geochemistry (MC&G) consisted of 18 scientific staff, 17 technical staff, 22 graded and administrative staff, and 9 people with postdoctoral appointments, all working on a total of well over 100 funded research projects. In addition, there were 18 Joint Program students, more than half of them in residence at Woods Hole.

Research in the department covers a broad spectrum of topics related to global climate change, biogeochemical cycles, ocean circulation, remote sensing of the ocean, environmental quality, trace metals, radioactive contamination, organic geochemistry, marine aerosols, photochemistry, sediment diagenesis, geochronology, and the geochemistry of seafloor hydrothermal systems. Common themes in much of MC&G research are quantification of the exchanges of material across the ocean's boundaries with air, land, and oceanic crust; identification of the materials added to the ocean; and characterization of the processes by which the ocean assimilates materials. Many projects are parts of large national and international programs such as the Joint Global Ocean Flux Study (whose national administrative office is housed in the department), the World Ocean Circulation Experiment, the Earth Observing System, the Ridge Inter-Disciplinary Global Experiment, and the Ocean Drilling Program.

Among the personnel changes that occurred during the year, Roger François was promoted to Associate Scientist with Tenure. The department bid farewell to two longtime members of the technical staff: Senior Research Specialist Hugh Livingston left to become the Director of the Marine Environment Laboratory in Monaco, and Research Specialist Ed Peltzer left to take a position at the Monterey Bay Aquarium Research Institute.

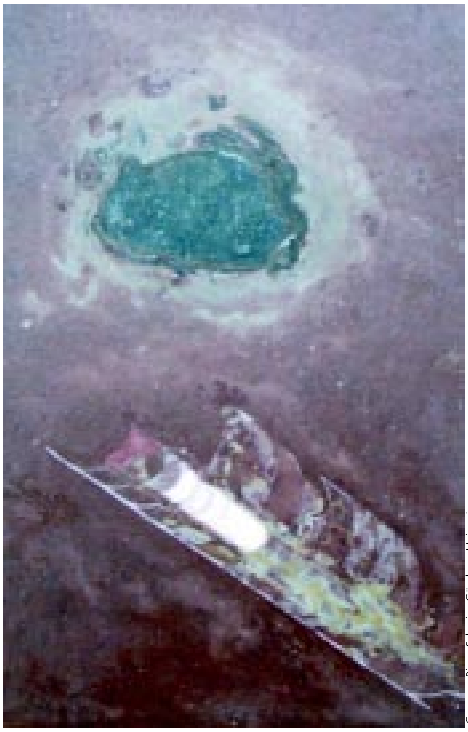
Several prestigious awards came to members of the department during the year: Senior Scientist Mark Kurz was elected a Fellow of the American Geophysical Union and received the new WHOI Edward M. and Betty J. Scripps Chair, Senior Scientist Fred Sayles was awarded the first Holger Jannasch Chair, Research Specialist Dempsey Lott received a Senior Technical Staff Award, and Adjunct Scientist Geoff Eglinton was co-recipient (with John Hayes of the Geology & Geophysics Department) of a Harold C. Urey Medal from the European Association of Geochemistry, and he also received a Royal Medal from the Royal Society.

—Michael P. Bacon, Department Chair

Extraterrestrial Material May Serve as Sediment Chronometer

Bernhard Peucker-Ehrenbrink, *Assistant Scientist*

Earth was formed about 4.5 billion years ago through accretion of material from the solar nebula. This accretion process has continued throughout the planet's history to the present, but at rates reduced orders of magnitude compared to the early accretion period. Extraterrestrial (ET) matter ranges in size from large, crater-forming asteroids and comets to particles smaller than 1 millimeter, collectively known as micrometeorites and cosmic dust. In many cases, ET matter is the oldest and most pristine material in the solar system, providing clues to its physical and chemical differentiation processes, as well as the evolution of life. Although micrometeorites were recovered from marine sediments during the 1872–1876 HMS *Challenger* expedition, ET matter in marine sediments has remained a curiosity for nearly a century. The discovery of sedimentary layers enriched in iridium and other platinum group elements at the 65-million-year-old Cretaceous-Tertiary (K-T) boundary and the K-T impact theory (that the collision of a large asteroid or comet with Earth resulted in mass extinctions) have revitalized interest in ET matter in marine sediments.



Courtesy Birger Schmitz, Göteborg University

Polished Orthoceratite limestone slab of lower Ordovician age (about 480 million years old) from the Thorsberg quarry near Kinnekulle, southern Sweden, with a fossil meteorite 8x7x6 centimeters in size and a fragment of an *orthoceratite* (fossil nautiloid with a straight, rather than spiral, chambered shell). This meteorite was found in the Sextummen bed at the top of the meteorite-bearing strata.

Part of my research is aimed at improving understanding of this ongoing accretion process, specifically temporal and spatial variation in the rate of ET matter delivery to Earth. The motivation for this research comes from the potential use of ET matter as a marine sediment chronometer, which would prove particularly useful for pelagic clays (sediments devoid of microfossils) that cover more than one third of the seafloor.

Imagine a constant rain of ET particles to the seafloor, diluted by calcareous and siliceous remains of marine organisms and fine-grained terrestrial material. This rain of ET matter can be used to determine rates of sediment accumulation if the flux of ET matter to the ocean floor is known and if minute amounts of ET matter can be detected using elemental and isotopic "fingerprints." In the simple case of a constant flux of ET matter to the seafloor, sediment accumulation rates are inversely correlated with the concentration of ET particles in sediments. The fact that a variety of independent sources from both inside (comets, asteroids) and outside (interstellar dust) the solar system contribute to the ET matter in marine sediments indicates that the flux of ET matter to Earth most likely fluctuates with time. We therefore need to reconstruct the spatial and temporal variations of the delivery rate before we can use ET matter as a chronometer. This can be done by comparing the concentration of ET matter in marine sediments of known age and accumulation rate. Fortunately, ET matter is chemically distinct from terrestrial material in marine sediments. Platinum group elements, for instance, are enriched 10,000-fold in ET matter compared to average crustal material. Moreover, the isotopic composition of the platinum group element osmium in ET matter is very different from that in seawater and average crustal material.

I have analyzed a suite of Cenozoic marine sediments for the concentration of platinum group elements and osmium isotopic composition in an attempt to calculate the flux of ET matter over the last 70 million years. The sediments analyzed were deposited very slowly and homogenized by organisms living at the seafloor. They therefore average the ET flux over periods of several hundred thousand years. The results of this National Science Foundation-funded project indicate that the flux of ET matter (about 40,000 tons per year) has remained more or less constant over the last 70 million years, if averaged over periods of several hundred thousand years. Only at the K-T boundary does the flux increase dramatically. More rapidly accumulated sediments average the ET matter flux over shorter time intervals and most likely will show variations in the rate of delivery of ET matter.

Erosion, alteration, and less precise age information make flux reconstructions for older sediments increasingly difficult. The recent discovery of meteorites some 480 million years old (lower Ordovician period) in a limestone quarry in southern Sweden therefore offers a rare glimpse into accretion history (see photo opposite). Fossil meteorites are extremely rare and only a handful of finds have been reported in the literature. In a collaborative project (funded by endowed WHOI assistant scientist support) with Birger Schmitz (Göteborg University in Sweden), who leads the Swedish fossil meteorite team, I have analyzed fossil meteorites and surrounding sediments for platinum group element concentration and osmium isotopic composition. The results of our analyses and model calculations indicate at least tenfold higher accretion rates of meteorites and cosmic dust during a roughly 1.5 million year period in the lower Ordovician compared to the present. Most likely, perturbations in the asteroid belt are responsible for this extra delivery of ET material to Earth. The sedimentary record may provide a largely unexplored paleorecord of accretion of ET matter on Earth. We hope that similar studies will help to better constrain the temporal and spatial variability in the flux of ET matter to Earth.

Aerosol Samplers, Sensors Developed for Buoy Deployment

***Edward R. Sholkovitz,** Senior Scientist*

Calling ourselves the "Dustbusters" (or Aero-Souls), four WHOI scientists and engineers—Edward Sholkovitz, Geoffrey Allsup, Richard Arthur, and David Hosom—are collaborating to design, build, and test aerosol samplers and sensors for deployment on ocean buoys. This effort is supported by the National Science Foundation.

Aerosols—particles suspended in air*—play substantial roles in the earth's radiation balance, climate and atmospheric chemistry. They are also involved in important biological and chemical processes in the oceans as these examples illustrate:

- The "Iron Hypothesis"—a current hot topic in oceanography—is built around the argument that phytoplankton production in large regions of the world ocean is limited by iron supplied by continental dust transported from Asia and Africa across large expanses of the Pacific and Atlantic Oceans.
- Injection of sea salt aerosols into the troposphere can affect the removal of ozone and the scattering of light and other forms of electromagnetic radiation.
- Formation of non-sea salt sulfate aerosols, derived from gaseous organic-sulfur compounds produced by certain ocean phytoplankton, influences the formation of clouds.

Ed Sholkovitz

The WHOI aerosol sampler is positioned on the right wing of the 22-meter (73-foot) Bermuda tower. The five filter modules (in a three/two stack) are mounted on the railing to the right.

Hence, sampling of aerosols near the ocean/atmosphere boundary is important with respect to understanding short and long term changes in climate, atmospheric and ocean chemistry, and ocean productivity. Because dust is deposited on the oceans in short, episodic events and in strong seasonal pulses, shipboard studies have rarely coincided with a dust deposition event. Use of buoys for more precise sampling offers the advantage of 3 to 12 months of continuous station time that can be correlated with satellite pictures of such events as dust outbreaks, biomass burning, algal blooms, and volcanic eruptions.

Our rugged sampler, designed to with-

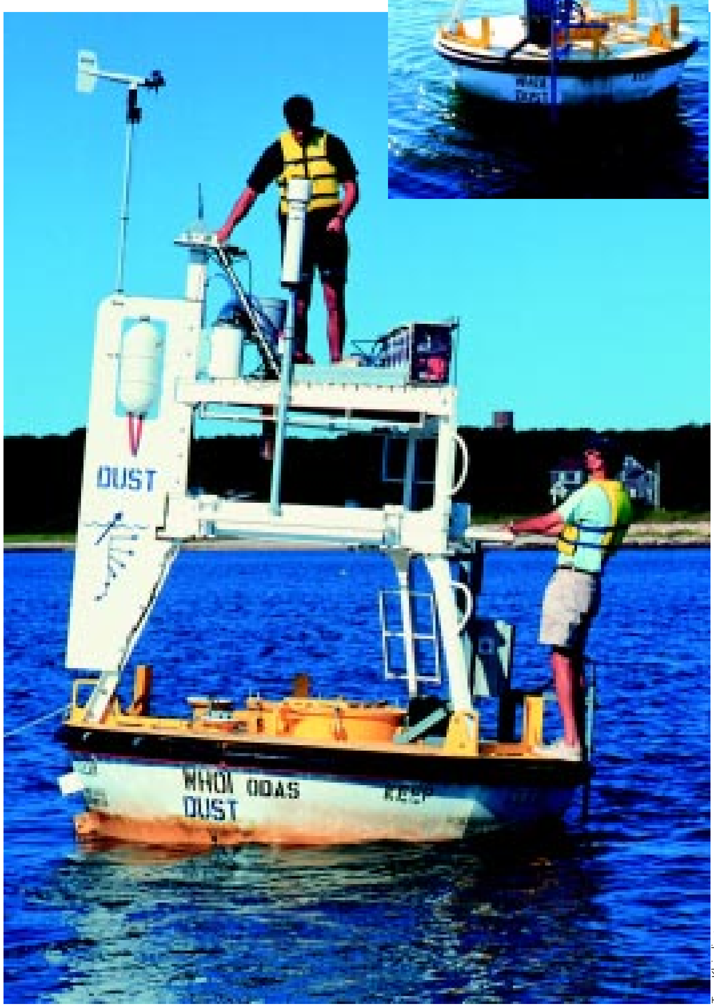
*Aerosols are solid or liquid particles suspended in air and ranging in size from 0.001 to over 100 millionths of a meter. The most common types are mineral dust; sea salt, organic, and fine cloud condensation particles; soot; and clouds. Natural aerosols are generated by oceans, desert, soil, vegetation, forest fires, and volcanoes. Aerosols also come from human activities such as gasoline, oil, coal, and charcoal combustion, forest and other biomass burning, cement production, smelting, and agriculture. Other aerosols form when gases are converted to fine particles in the troposphere.

stand breaking waves, strong winds, continuous motion, rainstorms, sea salt, films, and high humidity, collects a time-series set of aerosol-embedded 47-millimeter-diameter filters that are returned to the laboratory for chemical analyses.

To date, the sampler has performed as designed for seven months in the field: four months on the AEROCE (Atmosphere/Ocean Chemistry Experiment) tower in Bermuda (photo at left) and three months on a buoy moored off Woods Hole (photos at right). Both were instrumented for wind speed and direction, rate of precipitation, and rain detection. A wireless two-way communications modem was added to the buoy system, enabling us to monitor the sampling progress, to remotely change the sampling parameters, and to download the meteorological data.

One aspect of the Bermuda tower experiment was side-by-side comparison with more traditional aerosol samplers. In early October, both the WHOI and AEROCE samplers picked up a large pulse of particulate iron whose reddish brown color indicates an African origin.

Our next step will be to mount an engineering and science test on an open ocean buoy, and we are now designing a new carousel capable of generating a 50 sample set of aerosol-embedded filters from a single compact module. The Aero-Souls have also recently been funded to design, build, and test sensors to measure aerosol concentrations in real time from ocean buoys. X-ray fluorescence spectroscopy, a technique employed on the Mars rover, offers great promise for in situ analysis of aerosol elements. By using this nondestructive technique, we can distinguish between mineral dust and sea salt aerosols.



Tom Kleindinst

Ed Sholkovitz, right, and MIT UROP student Kevin McKenney adjust WHOI's autonomous aerosol sampler in Vineyard Sound off Woods Hole in August 1997. The five white filter modules are mounted on a 3-meter discus buoy. A vane keeps their air inlets (dark circular areas) into the wind. Other elements of the system include a control module, electrical and vacuum lines that lead from the control module to the back of the five filter modules, a rain gauge, a wind speed/direction sensor, a wireless modem with its antenna, and a fiber-optic carbon dioxide sensor system developed in the laboratory of David R. Walt (Tufts University).

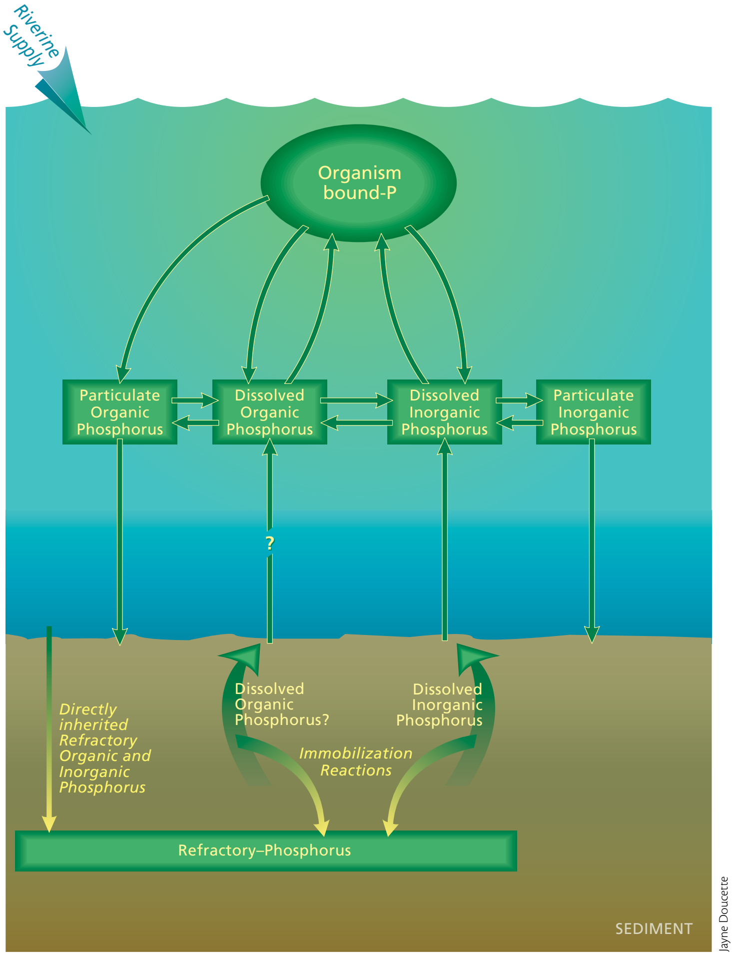
New Evidence for Phosphate Limitation in the Coastal Ocean

Kathleen Ruttenberg, Assistant Scientist

Phosphorus is an essential nutrient to all life forms. Phytoplankton, the floating microscopic plants of the sea, incorporate dissolved macronutrients such as phosphorus, nitrogen, and silicon, along with dissolved carbon and other essential substances, to build their tissues during photosynthesis. The diverse group of algae that make up the phytoplankton constitute the first link in the marine food chain. Because phosphorus, nitrogen, and silicon are in short supply relative to carbon in the ocean's surface waters, one or more of them may become totally consumed during periods of rapid algal growth, ultimately putting an end to production of more organisms. Because of their ability to limit biological productivity, these three nutrients are all candidates for the title of "limiting nutrient."

The prevailing wisdom in the scientific community is that nitrogen is the key nutrient limiting biological productivity throughout much of the oceans. However, recent studies expose this as an assumption not rigorously proven in marine systems, particularly in coastal environments. River runoff, stratification, and runoff- or current-driven bottom sediment resuspension can result in seasonally driven changes in the physical and chemical environment of the coastal zone. These factors directly impact the size and nature of the nutrient inventory, and algal species' response to the extremely variable coastal environment can be dynamic and highly complex. As evidenced by the vigorous debate about which is the limiting nutrient, we don't yet know enough about nutrient controls on productivity to construct descriptive models with confidence. We are even further from being able to make realistic predictive models.

An Office of Naval Research funded WHOI project combines geochemical and biochemical tools to explicitly evaluate the question of whether phosphorus can be limiting in the coastal ocean. Sources of phosphorus to the coastal water column

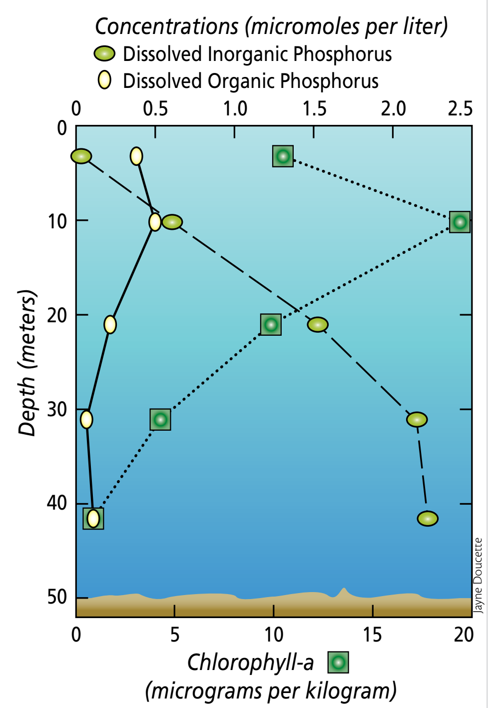


Schematic representation of the aquatic phosphorus cycle in the coastal ocean. Rivers are the most important external source of phosphorus to the ocean, delivering both particulate and dissolved forms. Phosphorus is also supplied to the coastal water column by diffusion out of sediments and by upwelling of deep water into shallow coastal areas (not shown). Phytoplankton first utilize dissolved inorganic phosphorus during photosynthesis. When this directly bioavailable form of phosphorus is depleted, the algae employ enzymes to cleave phosphate from more complex forms, creating dissolved inorganic phosphate from dissolved organic and particulate phosphorus. Phosphate can also be derived from particulate inorganic phosphorus by nonenzymatic, geochemical reactions. Phosphorus is typically efficiently recycled in the water column through processes of excretion by organisms and microbial decomposition of organic remains.

include river runoff and flux out of bottom sediments in addition to upwelling of offshore deep water and internal recycling due to grazing and microbial activity. This is in contrast to the open ocean where river runoff and bottom sources are unimportant. The various forms of phosphorus delivered to the coastal ocean by the sources listed above are: dissolved organic, dissolved inorganic, particulate organic, and particulate inorganic phosphorus. Not all forms of nutrients are immediately "bioavailable," that is, they are not directly assimilable by the photosynthesizing phytoplankton. For example, the phosphorus in dissolved organic compounds must be cleaved from the organic portion of the molecule before it can be taken up by an algal cell. Most often, the algae accomplish this by producing phosphate-cleaving enzymes that produce the simple dissolved molecule orthophosphate, which can be directly assimilated by algal cells. The project's key biochemical tool is measurement of the activity of one such enzyme, alkaline phosphatase. This enzyme is produced by phytoplankton only under conditions of phosphate limitation, and is therefore a marker for phosphate limitation.

Data on water column nutrients alkaline phosphatase and chlorophyll-a, a proxy for algal biomass, from cruises to the Eel River shelf off the California coast in spring and summer 1996 suggest that nutrient limitation shifted from nitrogen-limited in spring to phosphate-limited in summer. Dissolved inorganic nitrogen is present at limiting concentrations in spring, but is plentiful in summer. Summer is the only season when dissolved organic phosphorus concentrations exceed dissolved inorganic phosphorus concentrations in surface waters. In this situation the only source of dissolved phosphorus in surface waters is dissolved organic phosphorus. The maxima in dissolved organic phosphorus typically coincided with maxima in chlorophyll-a, and with significant alkaline phosphatase activity, most of which was associated with algal cells. The coincidence of low dissolved inorganic phosphorus, high dissolved organic phosphorus, plentiful dissolved inorganic nitrogen, high chlorophyll-a, and alkaline phosphatase activity in summertime surface water samples strongly supports the contention that phosphate was limiting biological productivity on the Eel River shelf at this time.

The regular occurrence of seasonal shifts in nutrient limitation in the coastal ocean would have important implications for the fundamental assumptions that underlie current qualitative and quantitative models of how nutrient limitation drives biological productivity in the coastal ocean. Ongoing research on nutrient limitation aims to further characterize the bioavailable nutrient pools, their sources, and the seasonal response of the phytoplankton community to different nutrient regimes driven by variable strength of the sources that deliver nutrients to the coastal ocean.



The profiles shown for Station G50 are typical of profiles observed at the 22 stations sampled during a summer 1996 Eel River Shelf cruise. High chlorophyll surface waters are depleted in dissolved inorganic phosphorus, and display a maximum in dissolved organic phosphorus.

Scientific research interests in the Physical Oceanography Department range in scale from broad, general circulation in ocean basins over years and centuries to mixing and dissipative processes that occur on scales of millimeters and seconds. Department staff members both conduct individual research programs and participate in large, cooperative interinstitutional and international field programs such as the World Ocean Circulation Experiment, Atlantic Circulation and Climate Experiment, Global Ocean Ecosystems Dynamics, Labrador Sea Convection Experiment, Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment, and the Coastal Mixing and Optics Experiment. Specific research includes theoretical and field work, analysis of observations, remote sensing, laboratory experiments, and analytical and numerical modeling.

The Department of Physical Oceanography consists of 34 scientific staff, 26 technical staff, 38 graded and administrative staff, 9 postdocs and 30 Joint Program students. There are 52 principal investigators working on some 200 research projects. During 1997, 95 new research proposals were submitted and 61 proposals were funded.

Assistant Scientist Sonya Legg, who joined the department in 1997, is working on a numerical investigation of deep convection in the Labrador Sea. Associate Scientists Roger Samelson and Mike Spall received tenure, and David Chapman was promoted to Senior Scientist. Associate Scientist Al Plueddemann, who served 16 months in Washington, DC as an Associate Program Manager at the National Science Foundation, returned to the department.

Department members were honored in several ways in 1997. Nelson Hogg received the W. Van Alan Clark, Jr., Senior Scientist Chair. Nick Fofonoff was awarded the American Meteorological Society's Stommel Research Award. Ray Schmitt received a Guggenheim Fellowship, which he is using to visit the University of Cambridge, England. Jack Whitehead was elected a Fellow of the American Geophysical Union and was also awarded the Paul M. Fye Senior Scientist Chair.

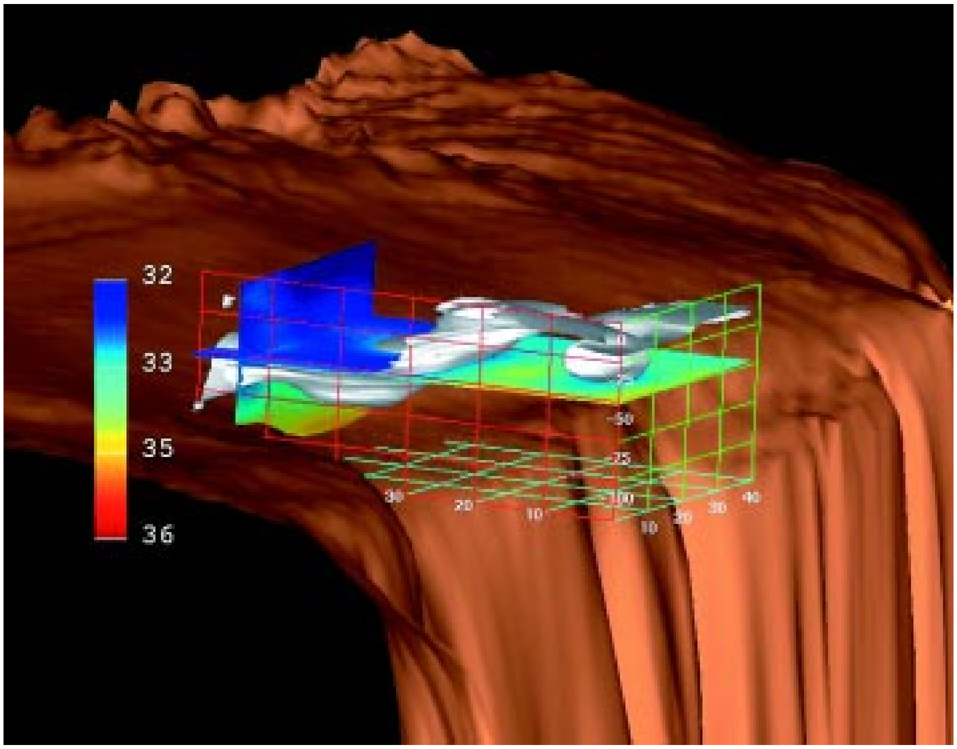
—Philip L. Richardson, Department Chair

SeaSoar Studies Show Complexity of Water Mass Interaction at the New England Shelfbreak Boundary

Glen Gawarkiewicz, *Associate Scientist*

The edge of the continental shelf south of New England is a region of sharply contrasting water masses. Over the continental shelf, cool fresh water is carried from the Gulf of Maine down to Cape Hatteras. Over the continental slope, warm saline water of Gulf Stream origin abuts the shelf water in a strong frontal zone. This front is in continual motion, with eddies rapidly forming along the front, winds blowing shelf water offshore, and Gulf Stream rings cleaving shelf water onto the continental slope. Because of the rapid time scale of these processes, traditional hydrographic sampling has allowed us only fleeting glimpses of the complexity of the frontal thermohaline (temperature and salinity) and velocity structure. A recent experiment, the Office of Naval Research Shelfbreak PRIMER study, has allowed us to see the front in a new light as a result of the high speed sampling possible with the WHOI SeaSoar instrument. SeaSoar is towed behind a research vessel at speeds of typically 8 knots—a huge advance over traditional hydrographic casts that require the ship to stop at each station.

During the PRIMER experiment, a joint physical oceanography/shallow water acoustics study, three cruises during May and July 1996 and February 1997 allowed WHOI



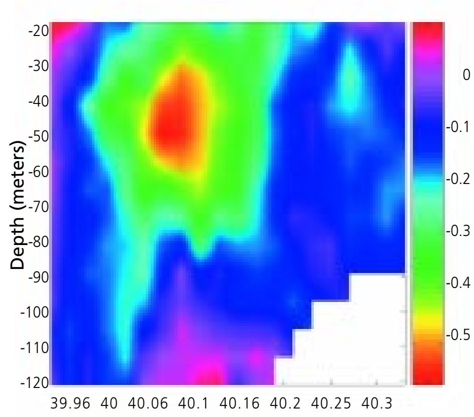
A view of the 33 parts per thousand salinity surface (shown in grey) from July 26, 1996, SeaSoar data taken at the edge of the continental shelf south of New England. The view is to the northeast, and horizontal distances in kilometers are marked along the grid with depths in meters. The shelfbreak front is apparent as the upward sloping surface near the 30 kilometer point in the red grid. Note that there is a small eddy of low salinity shelf water at the offshore edge of the section. The bathymetry, with vertical scale greatly exaggerated, is denoted by the brown underlying surface, and shows the abruptness of the change in bottom slope at the shelfbreak.

Digital camera image of R/V *Endeavor* (University of Rhode Island) deck operations during February 1997. Frank Bahr, left, of the SeaSoar group and *Endeavor*'s bosun have managed to recover the instrument just before another large wave crashes onto the fantail.

scientists and engineers to map the thermohaline structure of the shelfbreak front with unprecedented horizontal resolution. As a result, three-dimensional maps of the salinity, temperature, density, and velocity fields on a daily basis show the complexity of shelf and slope water mass interactions. For example, the figure opposite shows both small-scale eddies of shelf water, which are carried out over the continental slope, and bottom-trapped intrusions of saline slope water onto the continental shelf.

Perhaps the most dramatic findings to date concern the alongshelf jet that flows along the frontal boundary as a result of density differences between the two water masses. The maximum velocity within the jet ranged from 30 to 60 centimeters per second (half a knot to over a knot). A big surprise from the summer cruise was that the jet core was centered at a depth of 40 meters (see figure at right), beneath the seasonal thermocline (region of rapid temperature decline), as opposed to being surface-trapped. The shape of this jet has important implications for both how quickly frontal eddies form as well as the depth range over which the exchange between shelf and slope water masses may occur.

The winter cruise enabled us to determine how the front responds to strong wind forcing. It also allowed us to determine in how high a sea state SeaSoar could be operated (see photo above): The hard work and expertise of the WHOI SeaSoar group—Frank Bahr, Paul Fucile, Jerry Dean, Ellen Levy, Craig Marquette, and Al Gordon—made these new images of three-dimensional frontal structure possible.



A section of alongshelf (westward) velocity taken from the data illustrated in the figure on page 21. Note the bull's-eye shape of the jet core, centered at a depth of roughly 40 meters.

Satellite-Tracked Drifters Document Gulf Stream Meander Effects on Shelf Water Populations

Richard Limeburner, *Research Specialist*
Robert C. Beardsley, *Senior Scientist*

Since 1995, satellite-tracked near-surface drifters have been deployed over Georges Bank during winter to early summer. The primary objectives of this drifter program are to characterize the near-surface flow over the Bank, especially its temporal and spatial variability, and to integrate this information with other physical and biological measurements being collected in the US Global Ocean Ecosystems (GLOBEC) Georges Bank Study to help formulate a more coherent description of the Georges Bank ecosystem.

The transition between the homogeneous winter and stratified summer regimes is relatively fast (less than one month). In mid-January 1995, strong winds drove all Bank drifters south and southwest over the shelf break, where they became entrained in a warm-core ring.* During the winter-to-spring period, the mean flow over the Bank inside the 60 meter isobath was small. In early July, the unorganized winter regime switched to an eddy circulating clockwise over Georges Bank. We hypothesize that this transition is coupled to the change in the horizontal pressure force associated with low pressure over Georges Bank in winter and high pressure over the Bank in summer. The winter-summer transition to recirculation occurs approximately midway between the February-March temperature minimum and the September temperature maximum on top of the Bank.

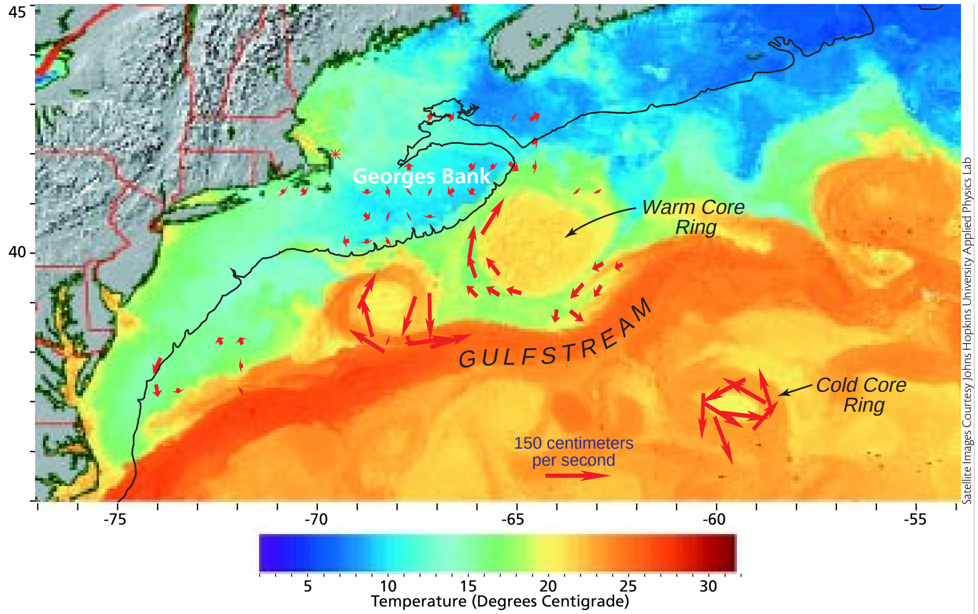
The 1997 drifter tracks have been com-

*Meanders or bends in the Gulf Stream often spin off ring-shaped circulation gyres. Rings that incorporate Sargasso Sea water from south of the Stream and end up north of the Stream are called warm-core rings because the core of the ring is warmer than surrounding waters; those found to the south and enclosing continental slope water are called cold-core rings.

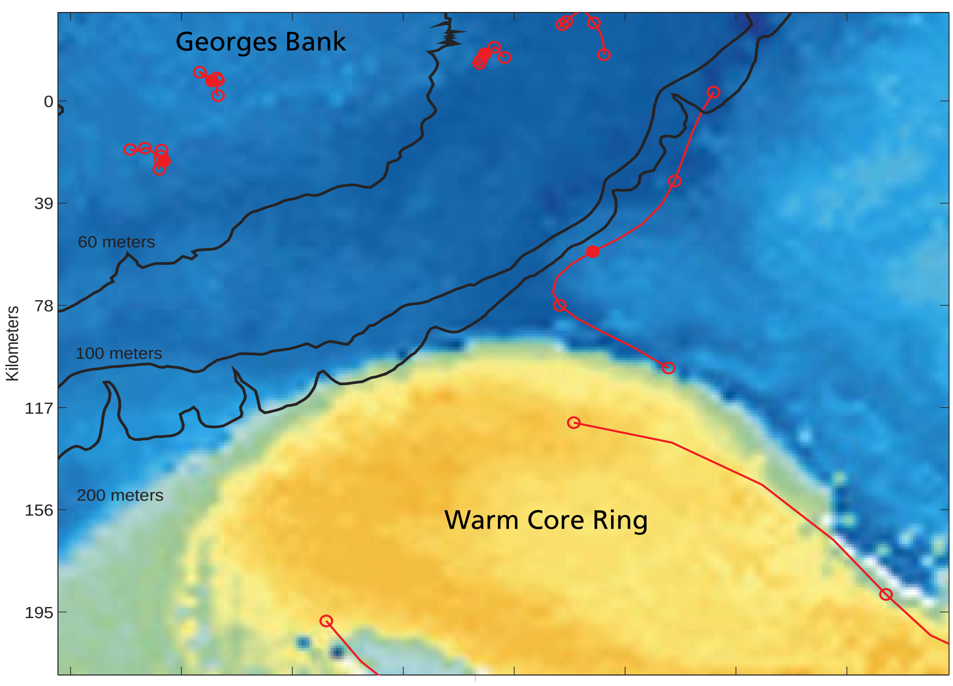
bined with satellite sea surface temperature (SST) data to enhance understanding of how warm-core rings affect Bank circulation and the loss of Bank water (and larval fish) along the southern flank. The June 13, 1997, satellite image of sea surface temperature shows two warm-core rings south of Georges Bank and one cold-core ring south of the Gulf Stream. All three of these rings contained drifters (mean velocities shown in red) deployed north of Georges Bank during January to June 1997. Our data indicate that warm-core rings approaching the Bank can entrain shelf water in the offshore direction in the northeast sector of the rings, and advect warm saline slope water onto the shelf in the northwest sector of the rings.

One example of a warm-core ring entrainment event is shown in the second image. Four-day-long drifter tracks are superimposed on the sea surface temperature field over the south flank of the Bank for May 13, 1997. On each track, day marks are shown as open circles, and a solid circle indicates the drifter position at the time of the satellite image. Although one drifter at the shelf break is clearly drawn offshore by the clockwise circulation of the warm-core ring, the other Bank drifters inshore of the shelf break appear unaffected by the ring. These and other examples show that the shelf water entrained by warm-core rings comes from a narrow depth band confined to the outer shelf. Thus the loss of Bank water and biota inshore of this zone to warm-core ring interaction is small.

Basic processing of the 1995–1997 drifter data is complete, and interested readers may obtain animations of the subtidal drifter positions, wind stress, and sea surface temperature at the U.S. GLOBEC WHOI web site, http://globec.whoi.edu/globec-dir/misc-data.html.



Satellite sea-surface temperature data combined with near-surface drifter velocities showing both warm- and cold-core rings near the Gulf Stream. The red arrows are near-surface drifter mean velocities within 0.5° squares for the five-day period centered on June 13, 1997, the time of the sea surface temperature image.

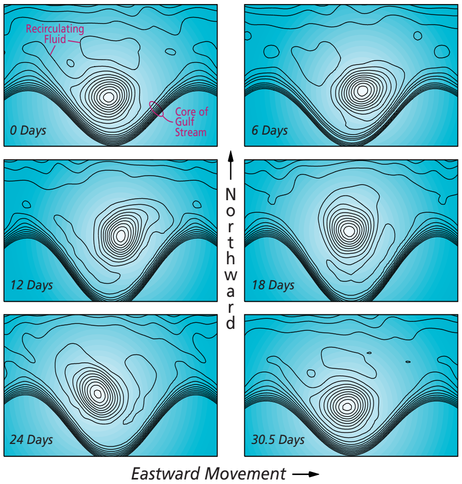


Sea surface temperature (see scale on upper figure) over the southern flank of Georges Bank on May 13, 1997, and drifter tracks over four days. Day marks are shown as open circles, and the closed circles show the location of a drifter at the time of the sea surface temperature image. One drifter is being drawn off the bank by a Gulf Stream ring.

Mathematical Advances Aid Interpretation of Float Paths

***Lawrence J. Pratt**, Associate Scientist*
***Audrey Rogerson**, Assistant Scientist*

Observations of currents in the ocean are often made by tracking drifters whose trajectories can be quite complicated. The lower left figure on page 24 shows an example. This instrument was launched in the Gulf Stream near Cape Hatteras and moved eastward, executing two loops as it went along. A number of physical features, including Gulf Stream meanders and spinoff eddies, might account for the looping motion. This makes it difficult to detect and distinguish be-

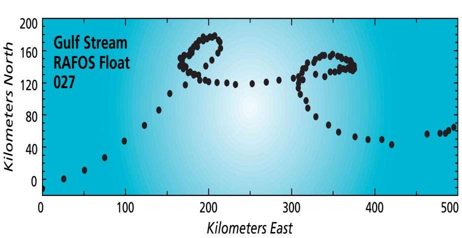


The different frames in this figure show streamlines in a computer model of the Gulf Stream at different times. The wavy sets of curves in the lower part of each frame correspond to the core of the Stream (which contains fluid moving from left to right). To the north lies a region of closed contours, corresponding to recirculating fluid. These frames are drawn in a frame of reference moving with the meanders .

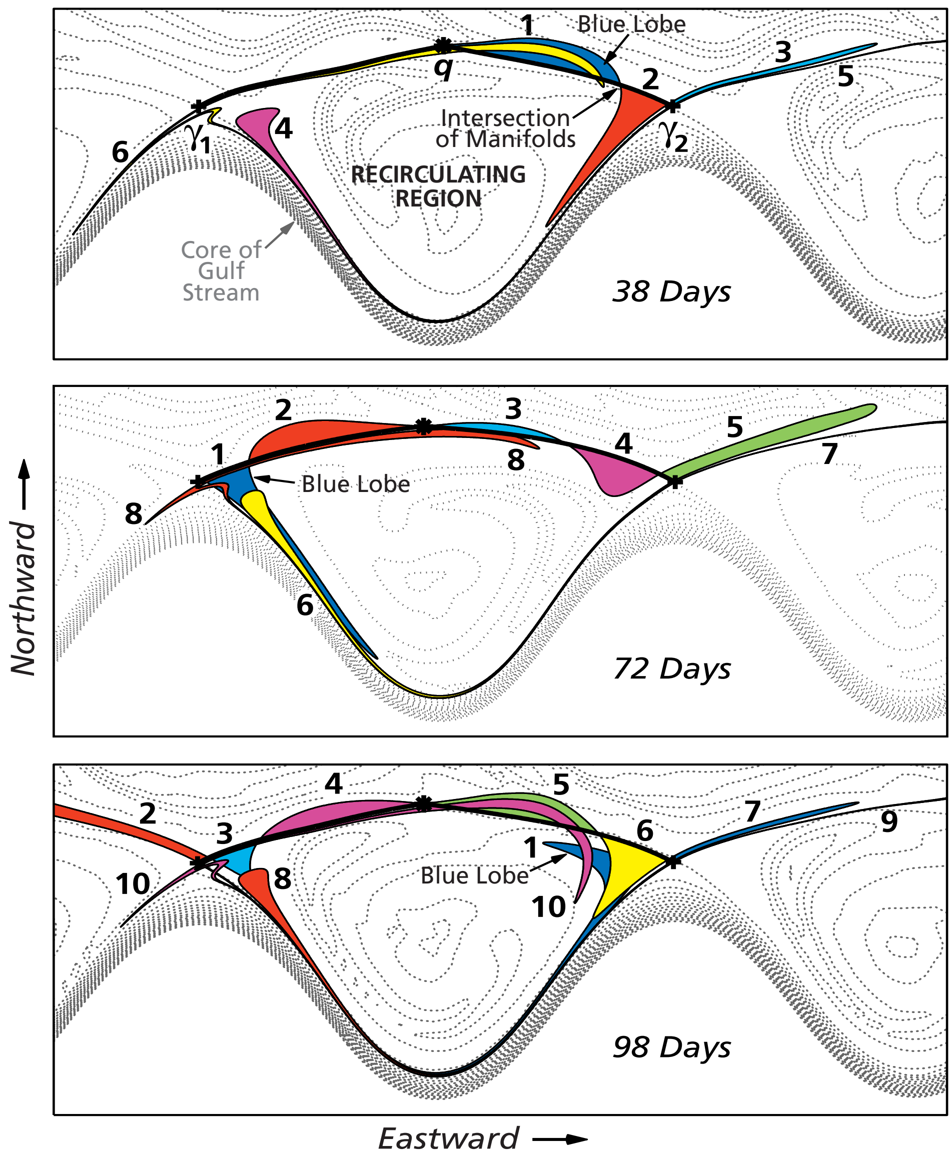
tween eddies, meanders, recirculations, and the like, but recent advances in the branch of mathematics known as dynamical systems has led to improvements in our ability to interpret float paths. For example, it is now known that certain hidden boundaries within the flow fields separate fundamentally different types of motion: For example, motion at the core of the Gulf Stream is predominantly wavy, while motion at the edges is generally looping.

The figure above shows these features in streamlines taken from a model of the Gulf Stream. In the center of the meandering flow the motion is wavy, while a patch of recirculating fluid rotates on the north edge. Farther to the north, the motion becomes weaker, but again wavy. When floats cross back and forth among these boundaries in a random or chaotic manner, it is generally a sign that intense mixing is taking place in the surrounding fluid. When floats stay on one side or the other of the boundary and exhibit relatively simple motion, there is very little mixing.

It is possible to identify fluid that crosses the hidden boundaries by finding special curves in the flow field called stable and unstable manifolds. The figure below shows some examples based on a flow field similar to the one shown at left. The manifolds (solid curves) intersect each other repeatedly. Fluid in the lobes that form between the intersecting curves is involved in the exchange described. The motion of the fluid can be followed by tracking lobes of the same color through the three frames in the figure, each of which represents a different time. For example, the blue lobe begins outside of the recirculating region (top frame) but is gradually pulled inside this region. In the final (lowest) frame, this lobe is next to the meandering core of the flow. The motion of fluid trapped in the colored lobes is chaotic. Lobe diagrams such as these serve as a tool for interpreting the complicated trajectories of ocean drifters and mapping out regions where water is being mixed. The Office of Naval Research has supported our efforts to improve understanding of drifter tracks.



The dotted path shows the eastward (left-to-right) motion of a RAFOS float launched in the Gulf Stream off Cape Hatteras.



The stable and unstable manifolds for the flow shown in the figure at left above. The colored blobs correspond to lobes of fluid trapped between the manifolds. This fluid passes in and out of the recirculations in a chaotic manner.

Marine Policy

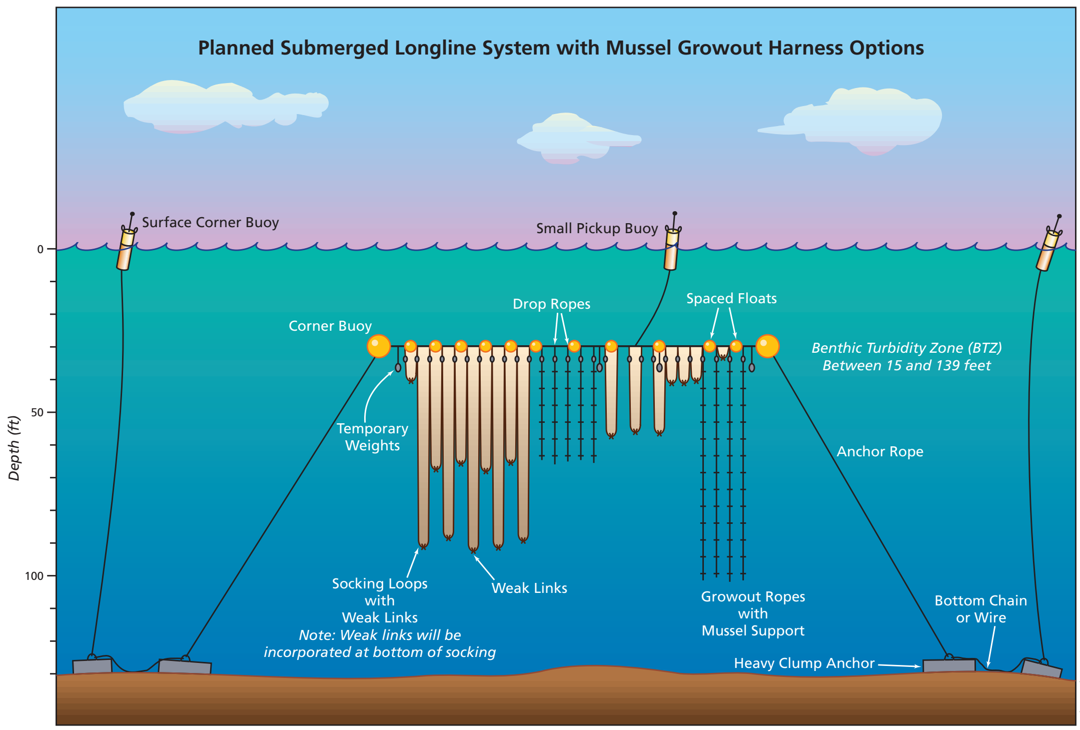
The Marine Policy Center (MPC) conducts social science research to advance the conservation and management of marine and coastal resources. The usefulness of such research depends upon its grounding in the best available scientific information. The work of MPC scholars integrates economics, law, and policy analysis with WHOI's basic strengths in the ocean sciences.

The conservation of biological diversity has been an important area of MPC research for several years. Current work in this area is organized around the general problem of selecting biological reserve sites to maximize species coverage subject to cost constraints and incomplete information about species distributions. One study completed in 1997 and published in the journal *Science* showed that accounting for differences in land prices improved efficiency—measured either by the number of species covered for a fixed conservation expenditure or the cost of covering a fixed number of species—by a factor of two to three.

MPC researchers also completed investigations in 1997 of the magnitude and sources of productivity change in four marine sector industries: fisheries, offshore oil and gas, shipbuilding, and cruise tourism. In both the fisheries and offshore oil and gas studies, the study approach involved modification of conventional models for measuring total factor productivity (TFP) to incorporate elements that have been omitted from previous studies because of data limitations. For the fisheries study, the new element was the fluctuation in open-access fishery stocks, which must be isolated from the effects of changes in capital and labor inputs to determine changes in the productivity of these production factors. The MPC study used data on New England groundfish and shellfish stocks over the past three decades. Omitting these data leads to the conclusion that TFP has declined at an annual average rate of 6.5 percent. Because fish stocks declined substantially more than industry output, however, inclusion of the stock effect yields the finding that TFP actually increased at an annual average rate of 2.8 percent. The study underscores the necessity of reducing fishing effort to keep renewable stocks at sustainable levels and, more generally, the importance of incorporating the stock effect in fisheries management policies designed to promote economic productivity.

For offshore oil and gas, the MPC study innovation was to develop a TFP model that accounts for the effects of changes in stock quality (increasing water depth and declining field size) as well as the standard factors of stock size (total oil and gas reserves), labor, and capital. The study used available industry-level data on offshore oil and gas exploration and production operations in the Gulf of Mexico for the period 1976–1995. Whereas the conventional TFP model suggests an average annual productivity decrease of 0.45 percent as total nonrenewable stocks are depleted, the MPC model produced a preliminary estimate of annual TFP gains that may be as high as 20 percent and are attributable to remarkable advances in exploration and drilling technologies that permit exploitation of smaller and deeper fields.

Studies of the shipbuilding and cruise industries were more constrained by data limitations but yielded significant insights as well. MPC researchers found that productivity has grown only slowly in the US shipbuilding industry in recent decades, and that advances in technology have been too narrowly channeled and in most cases too modest to afford US shipbuilders a strong competitive position in the world commercial market. These results reflect the industry's longstanding emphasis on Navy and other government orders, which have required a high degree of customization and have diverted attention from opportunities for significant improvement in the areas of building processes, management systems, and commercial marketing techniques. In the cruise industry, profitability eludes many operators in the North American market despite tremendous growth in the volume of sales since the 1960s. Because the demand for cruises is latent and highly sensitive to general economic conditions, fares have been deeply discounted during economic



Jack Cook

Marine Policy Center scholars are developing a framework for evaluating the commercial viability of longline mussel farming in a setting like the one illustrated here.

downturns, which has created a persistent expectation of low fares. MPC researchers conclude that two important consequences have been an unquantified but probably substantial US consumer surplus, in the form of continuing low fares, and a trend toward greater industry consolidation as operators strive to offset fare erosion by achieving greater economies of scale.

In September 1997, MPC became the host organization for a program that is laying the groundwork for increased habitat protection in the Gulf of Maine through the designation of marine protected areas (MPAs). The MPAs program was established and continues to be directed and substantially funded by the Gulf of Maine Council on the Marine Environment, which was formed in 1989 by an agreement among the Governors of Maine, Massachusetts, and New Hampshire and the Premiers of Nova Scotia and New Brunswick. The main elements of the current MPC program include evaluation of existing MPAs initiatives and mechanisms in the Gulf of Maine to ensure that future efforts build on what has already been accomplished, creation of a computer-based clearinghouse of existing data, and analysis of MPAs nomination processes used within the region and elsewhere as well as development of recommendations for a single process and a set of MPAs criteria for future use in the Gulf of Maine.

Another planned project featuring regional application of scientific research involves the deployment of a longline aquaculture harness in the US Exclusive Economic Zone off the coast of Massachusetts to test the engineering feasibility, biological productivity, and survivability of a longline for ocean culture of the blue mussel, *Mytilus edulis.* Scheduled to begin in 1998, the project will be a collaborative effort by MPC researchers, WHOI biologists and engineers, and a local commercial harvester and processor of blue mussels and other seafood products. MPC will develop a framework for evaluating the commercial viability of offshore farming using a longline technology, including a model of project economics, methods of risk assessment, and a model of supply and demand in the blue mussel market. The longline will be deployed at the "WHOI Buoy Farm," a scientific testing area near the mouth of Buzzards Bay.

John Porteous

It's spring blossom time at the Rinehart Coastal Research Center.

Rinehart Coastal Research Center

The Rinehart Coastal Research Center (RCRC) bridges department boundaries to encourage and initiate coastal research activities within the WHOI community. Endowment from Gratia Houghton Montgomery's generous 1996 gift has allowed significant increase in support for WHOI coastal research efforts. The Center has also stepped up its role in educational and outreach activities and is maintaining first-rate laboratory facilities and a fleet of small vessels for access to local waters.

Through a newly formalized annual call for proposals, RCRC solicits innovative, interdisciplinary research proposals that address coastal themes and are relevant to society's interest in the stewardship of coastal resources. Six grants were awarded in 1997, chosen from a group of 20 high-quality proposals.

One of the funded projects addresses the health of the critically endangered North Atlantic right whale. Michael Moore of the Biology Department developed a method to acoustically measure the blubber thickness of whales. His project entails field studies in the Bay of Fundy to determine whether blubber thickness is related to breeding success in right whales, whose reproduction rate is so low that the survival of the species is in jeopardy. An understanding of how body condition is linked to reproductive success may lead to improved policies to protect them.

In another of the RCRC awards, Lauren Mullineaux of the Biology Department teamed up with Stan Hart of the Geology Department to see whether larval organisms can be "fingerprinted" by measuring trace metals trapped within their shells during the early part of their growth. They will use WHOI's new Ion Microprobe, a sophisticated instrument that can identify trace elements within even a microscopic sample of an organism. If their approach is successful, they will be able to trace the origins of larval organisms back to particular embayments based on the ratios of trace metals found in their shells. This method could significantly improve our understanding of larval transport processes as well as provide important insights about the far-field impacts of contaminated harbors.

A third award went to an interdisciplinary team of paleoceanographers and physical oceanographers to establish a digital database from hard-copy reports of historic oceanic and atmospheric records taken aboard lightships. Between the 1870s and 1970s, manned lightships provided meteorological and oceanographic data for a number of sites along the coast. These data provide a unique opportunity to document long term changes in the coastal environment with particular relevance to climate change. This valuable database would be inaccessible to modern oceanographic analysis without the dedicated efforts of this WHOI team.

The Coastal Research Laboratory (CRL) contains advanced laboratory facilities for experimental work and for use as a staging area for coastal field programs, as well as housing administrative staff for RCRC and Sea Grant. A major upgrade of the lab was initiated in 1997, due in large part to a National Science Foundation (NSF) Major Research Instrumentation grant to Cheryl Ann Butman for construction of a new experimental flume. When completed, this 10-meter long, recirculating flume will be one of the world's most advanced recirculating flumes for studies of sediment transport, physical-biological interactions, and contaminant transport in the bottom boundary layer. This prestigious NSF award comes as a result of years of cutting-edge research by Butman and colleagues in the Coastal Research Center's experimental facilities. The cost-sharing between the Institution and NSF to support this new facility provides an excellent example of partnership betweeen public and private organizations to advance science.

RCRC maintains a small boat fleet for near-shore research. The RCRC fleet includes several vessels ranging in size from a 10-foot rowboat to the 24-foot R/V *Mytilus*, designed specifically for coastal research. In 1997, the *Mytilus* navigation and safety equipment was upgraded with the addition of a differential GPS navigation system and an Emergency Position Indicating Radio Beacon. *Mytilus* cut a broad geographical swath in 1997, working from the inlets of North Carolina to the Great Lakes, although most of its hours were logged in the coastal waters of southern New England.

The RCRC newsletter *Coastal Research* was redesigned for the September 1997 issue, and circulation was expanded to communicate RCRC's activities beyond the WHOI community. The newsletter contains information on RCRC sponsored events, facility and equipment updates, and discussions of issues relevant to RCRC interests. It also spotlights examples of the exciting coastal studies that WHOI scientists are performing. As part of its outreach effort, RCRC also sponsored a series of seminars during Coastweeks in the fall of 1997. These included lectures on topics ranging from the archaeology of the Nile delta to the ecology of Waquoit Bay, exemplifying the breadth of coastal research as well as the perennial interconnection between human activities and coastal processes.

Michael Moss

Carolyn Miller

Top photo: For a project designed to determine whether blubber thickness relates to breeding success, Michael Moore and Carolyn Miller watch for right whales from a small boat in the Bay of Fundy.
Bottom photo: The acoustic device that gives a reading on blubber thickness rests on a whale's back.

Sea Grant

The WHOI Sea Grant Program supports research, education, and outreach 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 1997, WHOI Sea Grant supported 16 concurrent research projects and 10 new initiative awards for project development. 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:

- investigating the reproductive strategies of the squid, *Loligo pealei*, and how those strategies contribute to genetic diversity,
- looking at flushing rates in estuaries as a way to determine the severity of human-induced problems such as nutrient loading or contamination of shellfish beds by harmful algal blooms,
- quantitatively measuring an ecosystem response to nutrient overloading from human population and land use changes,
- developing a stable isotope technique to detect the earliest stages of eutrophication caused by wastewater discharges,
- understanding schooling and feeding behaviors of bluefin tuna,
- developing visible and DNA-based markers for scallop identification to gain a better understanding of seeded scallop survival,
- gaining insight on the predatory behavior of ctenophores to determine their impact on commercially important fishes,
- understanding the factors that control the

life or death of larvae of soft shell clams, *Mya arenaria*, and their influence on population dynamics and distributions, and

• understanding the possible effects on marine mammals, aquatic birds, and other marine organisms exposed to pollutants in the marine environment.

In 1997 WHOI Sea Grant provided 24 months of support for graduate students through research awards. WHOI Sea Grant also sponsors qualified graduate students from throughout the Commonwealth in the Dean John A. Knauss Marine Policy Fellowship Program and other national fellowship programs sponsored by 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 from two local fairs are guest speakers at the opening night of the "Oceans Alive" series. And, for the sixth 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. Sea Grant is also represented on the advisory board for the joint venture of Turnstone Publishing Group, Inc. and WHOI to develop oceanographic curriculum materials for students in grades K-12.

Transferring the results of research and providing general marine-related information are important components of the WHOI Sea Grant Marine Extension and Communications Programs. 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. Both topics have been the focus of numerous workshops and outreach efforts with an emphasis on better management of resources at the local and regional levels.

In 1997, WHOI Sea Grant organized and sponsored, along with Massachusetts Coastal Zone Management, the Cape Cod Commission, and MIT Sea Grant, a workshop titled *Coastal Landform Management in Massachusetts*. The hands-on, two-day program featured presentations by local and state officials, regional planners, coastal geologists, and engineers, and used working groups to problem solve difficult coastal landform management dilemmas developed by a workshop planning committee. Detailed proceedings will be available in the spring of 1998.

WHOI Sea Grant provides information to broad audiences through a variety of means. One is our WHOI Sea Grant web site (http://www.whoi.edu/seagrant/). Others include the annual publication of a *Directory of Cape and Islands Coastal Outreach Organizations*; *Nor'easter* magazine, a publication of the six northeast Sea Grant programs; *Two if by Sea*, our joint newsletter with MIT Sea Grant; "Oceans Alive," our annual spring lecture series; and Coastweeks events including guided walks and field trips. Other communications efforts include disseminating Sea Grant and other marine-related videos and publications such as *Marine Science Careers: A Sea Grant Guide to Ocean Opportunities*, the biannual *WHOI Sea Grant Program Guide*, our publications catalog, and numerous other fact sheets, bibliographies, and reprints.

Tracey Crago

WHOI Sea Grant offers several programs and special events aimed at educating the general public about marine and coastal issues. In celebration of Coastweeks, Sea Grant organized a guided kayak "ecotour" in West Falmouth Harbor. Kayaks and instruction were provided by Kim Fernandes of Cape Cod Kayak.

Florida Department of Environmental Protection

Harmful algal blooms (HABs) are blooms of both microscopic and macroscopic marine algae that can wreak havoc on the marine environment in terms of economics (costly fish and shellfish kills and negative effects on tourism), public health (sickness or even death in humans who ingest afflicted fish or shellfish), and aesthetics (odors or discoloration of the water, the appearance of dead fish or shellfish on beaches). Research on red tide, caused by the toxic dinoflagellate *Alexandrium tamarense*, has been supported by WHOI Sea Grant for over two decades.

Special WHOI education events in 1997 included the fourth awarding of a WHOI Ph.D. and participation in the goodwill visits of the new *Atlantis* to New York City and Alexandria, Virginia.

Though the majority of degrees granted in our education program are from the MIT/WHOI Joint Program for graduate studies, a few students have completed degrees in a WHOI-only program because of the special nature of their doctoral studies. Amy Samuels, whose work on the social behavior of bottlenose dolphins with advisor Peter Tyack fell into this category, completed her work in 1997 and received her degree from Director Bob Gagosian at a special June 4 session of the WHOI Educational Assembly. Following the formal ceremony, a barbecue celebrated Amy's achievements as well as those of the 1997 Joint Program graduates, who received their degrees at the MIT commencement two days later.

During the *Atlantis* events in New York and Alexandria, as well as the Woods Hole "welcome home" festivities, Joint Program students served as knowledgeable and enthusiastic guides for tours of the ship. The mutually reinforcing excitement among the visiting K-12 students and teachers and the oceanography graduate students was a pleasure to witness!

The excellence of our students was recognized with several awards in 1997. Amy Samuels received the first F. G. Wood Award from the Society of Marine Mammalogy for the best student authored paper published in the society's journal, *Marine Mammal Science*, since the last biennial conference in 1995. Three of seven Outstanding Student Paper Awards for the Tectonophysics Section of the American Geophysical Union's December 1996 ses-

Degree Statistics

		1997	1968-97
WHOI	Ph.D.	1	4
MIT/WHOI	Ph.D.	20	335
MIT/WHOI	Sc.D.	1	30
MIT/WHOI	Engineer	0	54
MIT/WHOI	S.M.	10	92
Total Degrees Granted		32	515

Shelley Lauzon

Director Bob Gagosian, left, and Dean John Farrington flank new Ph.D. Amy Samuels and her advisor Peter Tyack at the special Educational Assembly called for Amy's graduation in June 1997.

Shelley Lauzon

MIT/WHOI Joint Program student Kelsey Jordahl talks with a group of students visting *Atlantis* during the ship's May port call in New York City.

Tom Kleindinst

National Science Foundation Graduate Research Traineeships Program Director Wyn Jennings, center, visited Woods Hole in the summer of 1997 to discuss WHOI's NSF Graduate Traineeship Grant in Coastal Ocean Processes with Associate Dean Judy McDowell and Dean John Farrington.

sions went to Joint Program students—to Emilie Hooft for her paper "Seismic Structure and Indicators of Magma Budget Along the Southern East Pacific Rise," to Stefan Hussenoeder for "A Comparison of Upper Crustal Structure Between Fast and Slow Spreading Ridges from Genetic Algorithym Seismic Wave Inversion," and to Laura Magde for "The Relationship Between Buoyant Mantle Flow, Melt Migration and from-the-Mantle Bouger Anomaly Patterns Observed Along the MAR from 33°N to 35°N."

This year we were very pleased to award the first Alfred G. Mayer and Katherine M. Townsend Postdoctoral Scholarship, which is intended to stimulate and encourage research in the field of biological oceanography, particularly with respect to salt marshes, the Great Barrier Reef, and deep ocean ctenophores. The first recipient is Mircea Podar, who completed a Ph.D. in the Department of Molecular Biology and Oncology at the University of Texas Southwestern Medical Center and is pursuing postdoctoral research on ctenophores in the laboratory of Richard Harbison in the WHOI Biology Department. She joins eleven other highly qualified scientists and engineers selected from among 134 applicants in 1997 to be Postdoctoral Scholars at WHOI.

Photos by Tom Kleindinst

Summer Student Fellows for 1997 worked in a variety of research and engineering situations from autonomous vehicle development (James Kinsey at top) to laboratory work (Kim Tugend at center) to salt marsh field work (Rob Dunn in foreground at bottom).

Two new posts were initiated in 1997 for WHOI faculty members. The Faculty Coordinator for Summer Undergraduate Programs is Ed Sholkovitz, Senior Scientist in the Marine Chemistry and Geochemistry Department, and Jack Whitehead, Senior Scientist in the Physical Oceanography Department, is faculty coordinator for the Geophysical Fluid Dynamics (GFD) Summer Study Program. Ed Sholkovitz directs the selection process for Summer Student Fellow and Minority Trainees and coordinates their summer programs. Twenty-three fellowships were awarded to 12 women and 11 men, four of them international and one minority, from an applicant group of 232. In addition, four Minority Trainees were appointed, and 32 Guest Students, both graduate and undergraduate, spent varying amounts of time at WHOI during the summer. The theme of the 39th summer GFD program was "Rotating Hydraulic Control," and it brought 42 staff and visitors to Walsh Cottage to interact with 10 graduate and postdoctoral fellows.

Judy McDowell completed her first year as Associate Dean, focusing primarily on graduate education and the MIT/WHOI Joint Program in particular. Physical Oceanographer Paola Rizzoli was appointed MIT Director of the Joint Program in August 1997, succeeding Marcia McNutt, who held the position for two years before moving west to become Director of the Monterey Bay Aquarium Research Institute in California. Paola Rizzoli and I are hard at work leading the arrangements for an external review of the Joint Program in 1998, the 30th anniversary year of the Joint Program.

Our alumni and alumnae are active in several activities, including career advice to students. In the fall, 1989 graduate Billy Spitzer, Curator for Education at the New England Aquarium, presented a special career seminar for Joint Program students and WHOI postdoctoral appointees. Members of the Alumni and Alumnae Association of the MIT/WHOI Joint Program are assisting with plans for an anniversary celebration in the fall of 1998 that will include festivities both in Cambridge and in Woods Hole. We look forward to sharing this memorable anniversary with members of the broader WHOI community.

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

Shelley Lauzon

Roger LeMoine

Shelley Lauzon

A joyful crowd gathered (large photo) on the Woods Hole pier April 11, 1997, to welcome the new research vessel *Atlantis* on its first call in home port. The ship left Mississippi March 25 (top right photo) following a send-off luncheon for guests that included Mississippi Senator Trent Lott and shipyard president John Dane (top left photo). While pierside outfitting was underway, posters and video equipment were installed in the ship laboratories and navy polo shirts were handed out to members of the crew, students, scientists, administrators, and other employees who would be presenting ocean science to hundreds of visitors in three ports.

Vicky Cullen

Shelley Lauzon

Jeff Watts

Tom Kleindinst

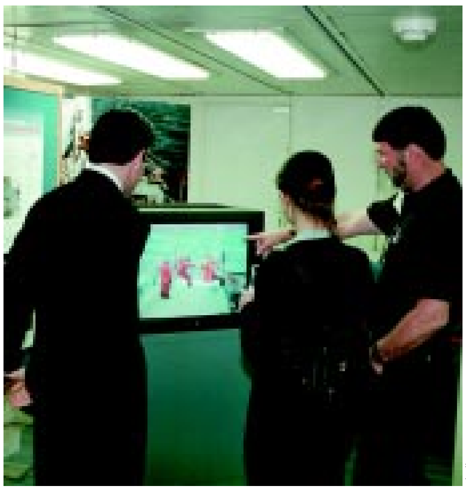
Shelley Lauzon

Tom Kleindinst

Atlantis *Events*

Roger LeMoine

Jeff McEvoy



Shelley Lauzon

Following introduction of the ship to employees, Associates, education program graduates, students, Trustees, and Corporation Members in Woods Hole, *Atlantis* traveled to New York City. From May 14–16 the "blue shirts" conducted tours, set up self-guided tours, and addressed visitors at stations among the posters and video monitors, welcoming a variety of students and visitors from the New York area aboard ship.

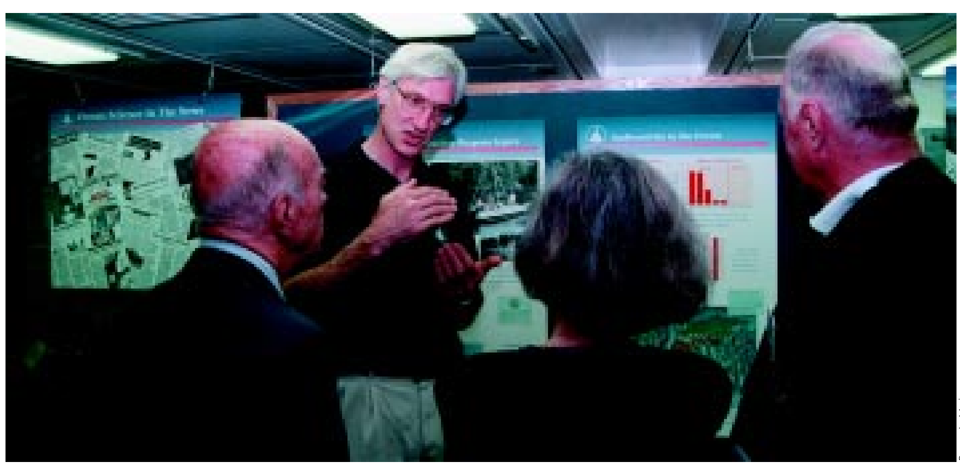
Tom Kleindinst

Justine Gardner-Smith

Jeff Watts

Shelley Lauzon

Justine Gardner-Smith



Roger LeMoine


Jeff McEvoy


Shelley Lauzon

Vicky Cullen


Jeff McEvoy

The last "*Atlantis* event" took place in the Washington, DC, area May 18–21 with a port call in Alexandria, Virginia. The festivities occupied not only the ship but also a large pierside tent that accommodated a dinner, receptions, and other activities. Guests included the President's Science Advisor, Cabinet Members, Senators, Representatives, Congressional staff, funding agency personnel, and many friends and associates of the Institution.


Jeff Watts


Jeff Watts


Jeff Watts


Jeff Watts

R/V Atlantis & DSV Alvin

Total Nautical Miles in 1997—20,391
Total Days at Sea—208
Total Number of Alvin *Dives—97*

A large crowd welcomed *Atlantis* when the ship made its first call in home port on April 11. Subsequent celebrations of the new ship's delivery in Woods Hole, in New York City May 14 to 16, and in Alexandria, VA, May 18 to 21 have collectively come to be known as "the *Atlantis* events" (see pictures on the cover, pages 31-33, and elsewhere through the annual report). An inhouse period of outfitting the new ship followed, including integration of *Alvin* aboard for the first time.

The first science mission took the ship to Bermuda for *Alvin* certification following the submersible's routine overhaul period. Two voyages to the Mid-Atlantic Ridge for biological work at seven hydrothermal vent sites came next before the ship transited the Panama Canal to begin investigations in the Pacific. Work along the California coast for bioturbation studies was followed by interdisciplinary studies on the Juan de Fuca Ridge, some of which included the vehicles *Jason*, *Argo II*, and *DSL-120* in addition to *Alvin*. The year's last two cruises took *Atlantis* to 9° North on the East Pacific Rise for continuation of a long-term study of the biology and geochemistry as well as light emission and further biological studies of hydrothermal vent systems.

Doug Weisman

In a rare moment with all three WHOI research vessels in port on April 21, 1997, *Knorr* is in the foreground with *Oceanus* and the new *Atlantis* on the opposite side of the pier.

Chief scientists for 1997 were: R. Pittenger (Voyage 1, Legs I–III and Voyage 2, Legs I–II); B. Walden (2–III, 3–I with 16 dives, and IX); D. Fornari (3-II, 2 dives); R. Vrijenhoek, Rutgers Univ. (3-III, 18 dives); C. Smith, Univ. of Hawaii (3-V, 3 dives); A. Bowen (3-VI); J. Delaney, Univ. of Washington, and C. Fisher, Pennsylvania State Univ. (3-VII, 5 dives); H. P. Johnson, Univ. of Washington, and K. Becker, Univ. of Miami (3-VIII, 11 dives); R. Lutz, Rutgers University (3-X, 18 dives); and A. Chave (3-XI, 23 dives).*

R/V Knorr

Total Nautical Miles in 1997—37,957
Total Days at Sea—265

The *Knorr* crew spent a stormy winter in the North Atlantic conducting a January meteorological sampling cruise for the international Fronts and Storm Tracking Experiment (FASTEX) and a February–March cruise in the Labrador Sea designed to study water mass transformation events. During April and May, the ship was engaged in three mooring and sampling voyages for the Coastal Mixing & Optics experiment in the Western North Atlantic as well as one cruise for the US Global Ocean Ecosystems Dynamics (GLOBEC) Program on Georges Bank. Following the setting of several moorings in the North Atlantic, Knorr was engaged in three extensive hydrographic transects for the World Ocean Circulation Experiment (WOCE) Atlantic Circulation and Climate Experiment (ACCE), and the ship hosted the last WOCE-ACCE field program cruise from October 14 to November 20. The ship's final 1997 cruise included a SeaBeam survey and engineering tests of a side-scan sonar system for the Naval Oceanographic Office.

Chief scientists for 1997 were: O. Persson, NOAA (147-IV); R. Pickart (147-V & 151-III); A. Williams (149-I & III); J. Irish (149-II); W. Gardner, Texas A&M Univ. (150); T. Rossby, Univ. of Rhode Island (151-I); L. Talley, Scripps Inst. of Oceanography (151-II); T. Joyce (151-IV); J. Kemp (153); M. Swartz (154-I); R. Curry (154-II); and D. Joseph, Naval Oceanographic Office (155).*

Sarah Zimmermann

After clearing the staging area of ice, Marshall Swartz, right, and Shelley Ugstad help guide the CTD package during an R/V *Knorr* winter 1997 Labrador Sea deployment.

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

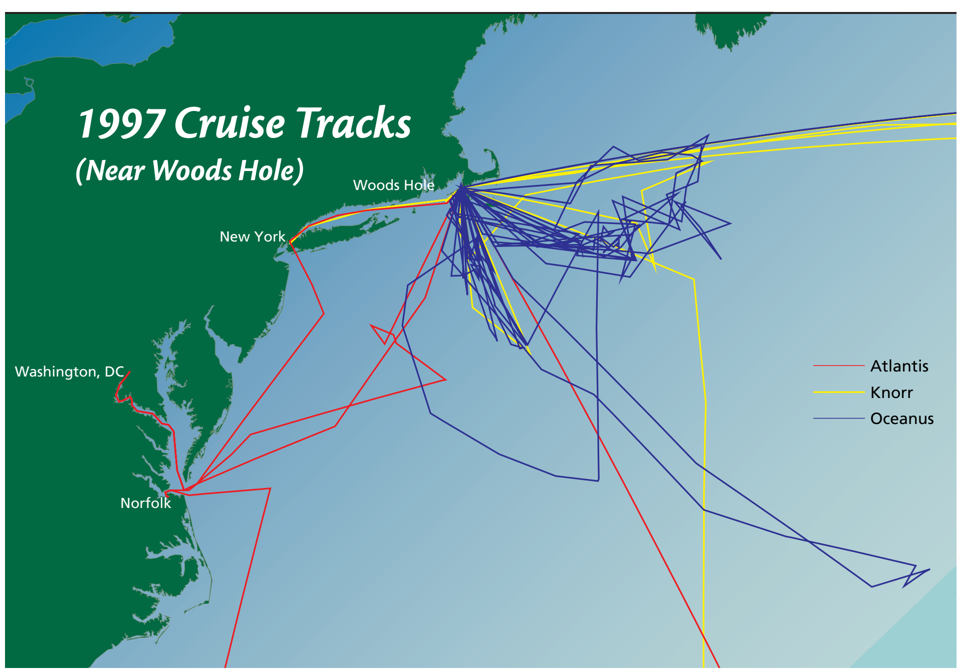
Jack Cook and Lane Abrams

R/V Oceanus

Total Nautical Miles in 1997—13,641
Total Days at Sea—202

The year began for *Oceanus* with a cruise for the Coastal Mixing & Optics Experiment. This was the first of four voyages for this experiment that included mooring and retrieving instruments on the continental shelf south of Nantucket in January, May, June, and August as well as a dye tracer experiment in July. Scientists of the US GLOBEC Georges Bank made extensive use of the ship for mooring work, hydrography, plankton/larval studies, and SeaSoar surveys from January through May, in June, and in August. Other work included biological and chemical studies in the Sargasso Sea, air-sea gas exchange and surface wave measurements, instrument and vehicle tests, and mooring recovery for the Synoptic Ocean Prediction program.

Chief scientists for 1997 were: A. Williams (295 & 310); R. Schlitz, NOAA/NMFS (296 & 311); P. Chisholm, MIT (297); E. Horgan (298); C. Lee (299); P. Wiebe (300); G. Lough, NOAA/NMFS (301 & 303); A. Bucklin, Univ. of New Hampshire (302); R. Houghton, Lamont-Doherty Earth Observatory (304); S. Anderson (305); W. Strahle, USGS (306); E. Bock (307); F. Sayles (308); J. Ledwell (309); S. Worrilow (312); and J. Bellingham, MIT (314).*



Jack Cook and Lane Abrams

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Mechanical Shop Supervisor Bob McCabe briefs board members on a tour of WHOI facilities during the fall 1997 Trustee and Corporation meetings.

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As of December 31, 1997

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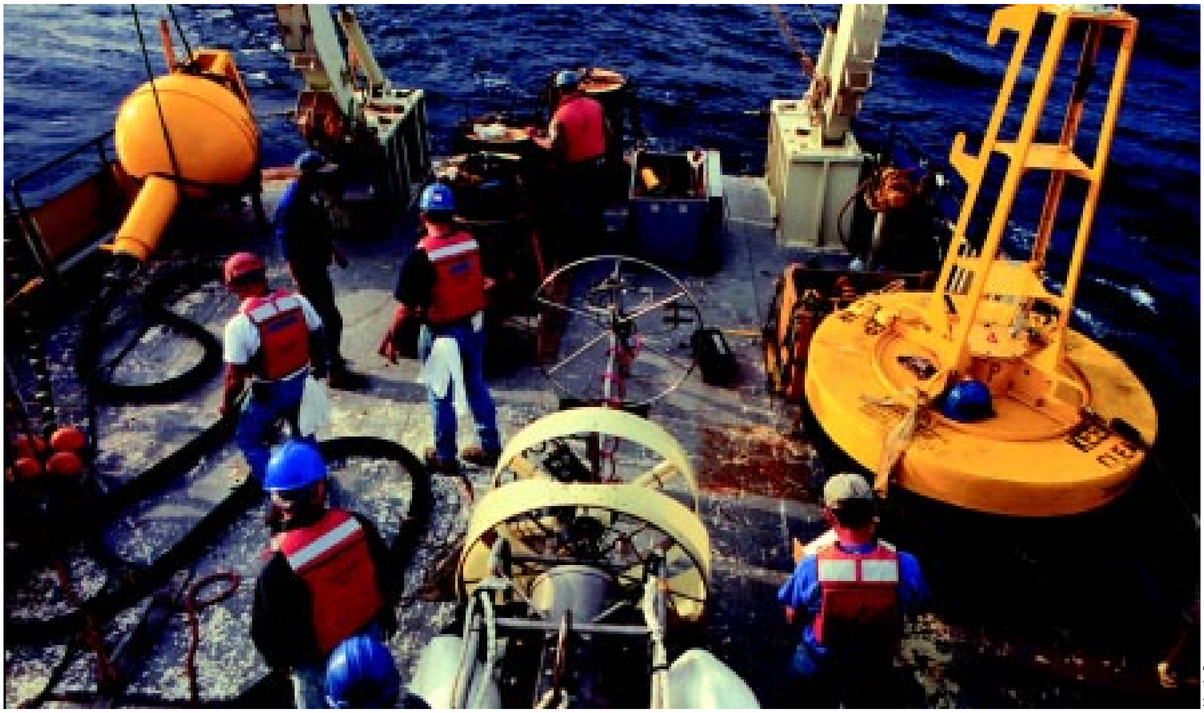
Martin Bowen

Oceanus crew and WHOI engineers prepare to deploy an autonomous vehicle docking station designed for the MIT vehicle *Odyssey*. The docking station in the center foreground sends data taken by the vehicle to the yellow surface buoy at upper left via the black S-tether for transmission via satellite to laboratories ashore.

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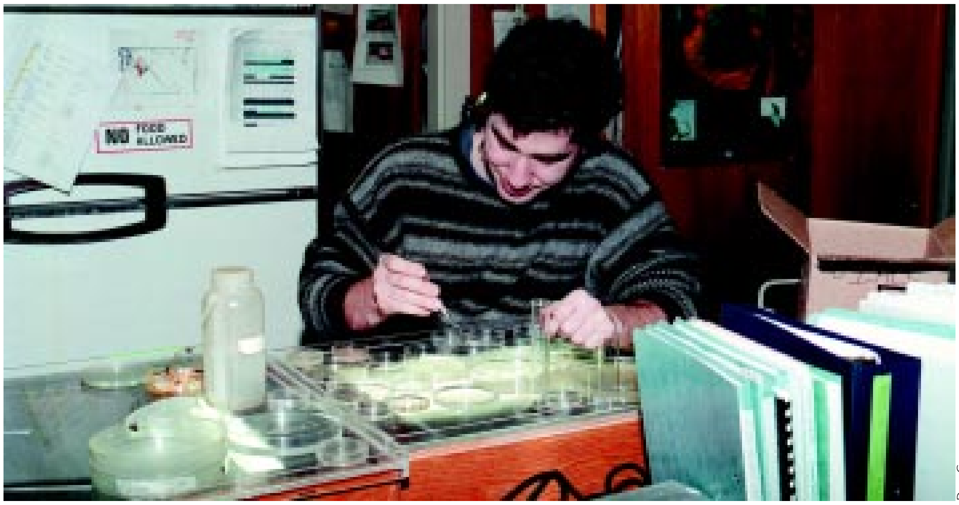

James Brien sorts plankton samples in Larry Madin's Lab.

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Following completion of the submersible's overhaul in preparation for joining *Atlantis* for the first time, the *Alvin* group gathered aboard the new ship for a group portrait.

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Ann C. Henry
Department Administrator, Applied Ocean Physics and Engineering

Dave Gray, one of the 20-year service honorees at the 1997 Employee Recognition Ceremony, receives a boutonniere from Nancy Barry.

Nancy L. Hossfeld
Assistant Manager of Information Services
Kevin F. Hudock
Benefits Administrator
Michael Hurst
Senior Accountant
Charles S. Innis, Jr.
Security Officer
Barbara J. Inzina
Director of Computer Information Services
Richard B. Kendall
Procurement Representative II
Judith L. Kleindinst
Department Administrator, Biology
Kathleen P. Labernz
Human Resources Manager
Michael P. Lagrassa
Assistant Procurement Manager
Dennis Lander
Network Group Leader
Shelley M. Lauzon
Senior News Officer
Katherine A. Madin
Curriculum Coordinator
Stacey L. Medeiros
Manager of Budgets and Financial Analysis
Laura A. Murphy
Payroll Manager
Steven M. Murphy
Grants Administrator II
Thomas G. Nemmers
Development Officer
Jane B. Neumann
Director of Development
Maureen F. Nunez
Controller

Maryanne F. Pearcey
Department Administrator, Geology and Geophysics
A. Lawrence Peirson III
Special Assistant to the Associate Director of Education
Claire L. Reid
Executive Assistant to the Director Of Research
Lesley M. Reilly
Development Officer
Patricia E. Remick
Administrator for Office Programs
R.D. Rudden, Jr.
Assistant Controller
Sandra A. Sherlock
Senior Procurement Representative
Marcella R. Simon
Registrar & Education Office Administrator
David Stephens
Manager of Accounts Receivable
Maurice J. Tavares
Manager, Grant and Contract Services
Donna Weatherston
Manager of Government Regulations
Julia G. Westwater
Assistant Registrar
Mary A. White
Procurement Representative II
Elaine M. Wilcox
Retirement Benefits Administrator
John A. Wood, Jr.
Procurement Representative II

Dianna M. Zaia
Manager of Treasury Operations

Administrative Support Staff

Pierrette M. Ahearn
Steven W. Allsopp
Lisa A. Arnold
Linda Benway
Gary Berntson
Suzanne M. Bolton
Trish Bonnevier
Patricia C. Brennan
Gail F. Caldeira
Lee A. Campbell
James J. Canavan
Maureen E. Carragher
Sherry H. Carton
Leonard Cartwright
Bruce R. Cole
Aganoris Collins
John E. Cook
Dina M. DiCarlo
Lisa M. DiPalma
Jayne H. Doucette
Edward F. Dow
Kittie E. Elliott
Lynne M. Ellsworth
Glenn R. Enos
Gregory D. Flick
Gloria B. Franklin
Melissa Gately
Lucinda J. Gathercole
Ruth E. Goldsmith
Helen E. Gordon
Pamela J. Goulart
David L. Gray
Mark V. Hickey
Channing Hilliard
Jane A. Hopewood
Lisa M. Hunt
Robin L. Hurst
Thomas N. Kleindinst
Lynn M. Ladetto
Dennis E. Ladino
William D. Lambert
Donna L. Lamonde
Tariesa A. Lemmon
Samuel J. Lomba
Helene J. Longyear
Richard C. Lovering
Linda E. Lucier
Molly M. Lumping
Ann McIntyre
Fay L. McIntyre
Patricia A. McKeag
Sandra E. Murphy
E. Paul Oberlander
Sharon J. Omar
Kathleen Patterson
Isabel M. Penman
Jeanne A. Peterson
Clara Pires
Jeannine M. Pires
John Porteous
Lisa M. Raymond
Dena Richard
Peggy A. Rose
Emily H. Schorer
Deborah K. Shafer
Sandra L. Sherlock
Timothy M. Silva
Nancy Stafford
June E. Taft
Mildred Teal
Judith A. Thrasher
Susan F. Tomeo
Dacia Tucholke
Susan E. Vaughan
Carlos Velez III
Robert J. Wilson

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

Lawrence T. Bearse
Master, R/V Oceanus
Richard S. Chandler
Submersible Operations Coordinator
Ernest G. Charette
Assistant Facilities Manager
Gary B. Chiljean
Master, R/V Atlantis
Joseph L. Coburn, Jr.
Marine Operations Manager
Arthur D. Colburn III
Master, R/V Knorr
Hugh D. Curran
Chief Engineer, R/V Atlantis
William A. Eident
Chief Engineer, R/V Oceanus
Stephen M. Faluotico
Deep Submergence Vehicle Pilot
Kevin C. Fisk
Chief Engineer, R/V Atlantis
Richard E. Galat
Facilities Engineer
Matthew C. Heintz
Deep Submergence Vehicle Pilot
J. P. Hickey
Deep Submergence Vehicle Pilot
Paul C. Howland
Master, R/V Atlantis
Lewis E. Karchner
Safety Officer
Barbara J. Martineau
Marine Operations Administrator
William E. Mckeon
Facilities Manager
Everett McMunn
Master, R/V Oceanus
Donald A. Moller
Marine Operations Coordinator
Theophilus Moniz III
Marine Engineer
Richard F. Morris
Chief Engineer, R/V Oceanus
David I. Olmsted
Boat Operator
Terrence M. Rioux
Diving Safety Officer
Manuel A. Subda
Marine Personnel Coordinator
Ernest C. Wegman
Port Engineer
Leo R. Wells
Property Administrator
Robert L. Williams
Deep Submergence Vehicle Pilot

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

Michael T. Aiguier
Thomas M. Allen
Douglas H. Andrews III
Carrie A. Bachand
Wayne A. Bailey
Courtenay Barber III
Mitchell G. Barros
Linda J. Bartholomee
Robert Bastarache
Gunter H. Bauerlein
Richard C. Bean
Harold A. Bean
Eric M. Benway
Robert Bossardt
Thomas A. Bouche
John R. Bracebridge

Allan Brierley
Edmund K. Brown
Mark E. Brown
Mark Buccheri
Frederick E. Bull
Sean C. Burke
Raymond A. Burke
Michael B. Butler
Richard J. Carter
Gary S. Caslen
John A. Cawley
John P. Clement
Jeffrey D. Clemishaw
Charles Clemishaw
Alberto Collasius, Jr.
TorII M. Corbett
Gregory Cotter
Jerome M. Cotter
John A. Crobar
Donald A. Croft
William B. Cruwys
Judith O. Cushman
Hugh B. Dakers
Sallye A. Davis
Mark C. De Roche
Pearl R. Demello
Craig D. Dickson
Francis J. Doohan
Gardiner S. Doughty
James H. Dufur, Jr.
William J. Dunn, Jr.
Daniel B. Dwyer
Richard Edwards, Jr.
Geoffrey K. Ekblaw
Deidra L. Emrich
Jovinol Fernandes, Jr.
Peter F. Ferraro
Anthony Ferreira
John Fetterman
Michael J. Field
Louis W. Fox III
Joseph Giacobbe
Guy R. Gibson
Edward S Good
Jerry M. Graham
Edward F. Graham, Jr.
Robert J. Greene
Christopher M. Griner
K.I. Faith Hampshire
Douglas Handy
Patrick J. Harrington
Robert W. Hendricks
Patrick J. Hennessy
Penelope Hilliard
Marjorie M. Holland
Alan J. Hopkins
Sharon L. Hunt
Philip M. Hurlbutt
Peter Hutchins
Lawrence F. Jackson
Christopher B. Jewett
Paul A. Kay
John K. Kay
Kevin F. Kecy
Fred W. Keller
Sara J. Kustan
John P. Kutil
Donald C. Leblanc
Paul E. Leblanc
Jeffrey Little
Glenn R. Loomis
William H. Lynch
James Macconnell
Piotr Marczak
Paul Martin
Kenneth Martin
Eduwiges L. Martinez
Keith Massa
J.D. Mayer
Joseph L. Mayes
Robert A. McCabe
Napoleon McCall, Jr.
Emily L. McClure
David McDonald
Katherine E. McMaster
Robert H. McMurray
Horace M. Medeiros
Anthony D. Mello
Brian J. Mercier
Mirth N. Miller
Maureen E. Moan
Patrick S. Mone
John D. Morgan
Christopher D. Morgan
Norman E. Morrison
Jose S. Mota
Jay R. Murphy
John R. Murphy, Jr.
Richard M. Nolan
Matthew G. O'Donnell
Charles A. Olson
Brian M. O'Nuallain
Patricia L. Pasanen
Sheila T. Payne
David C. Peterson
Richard D. Pierce
Patrick M. Pike
Kathleen A. Ponti
Edward S. Popowitz
Douglas R. Quintiliani
Joseph Rodriques
John P. Romiza
Steven Rossetti
James R. Ryder
Lewis J. Saffron
Michael J. Sawyer
Robert W. Schreiter
Kent D. Sheasley
George P. Silva
Jennifer J. Sirois
Richard Smith
Debra A. Snurkowski
Andrew E. Sokolowski
Steven P. Solbo
William F. Sparks
Robert G. Spenle
Mark L. St. Pierre
Joshua G. Stephenson
Jeffrey M. Stolp
Elizabeth Suwijn
Wayne A. Sylvia
William R. Tavares, Jr.
Anne M. Taylor
Kevin D. Thompson
Maeve Thurston
Anne Toal
Philip M. Treadwell
Stephen Vetra
Herman Wagner
Stephen A. Walsh
Richard H. White
Robert Wichterman
Eileen R. Wicklund
Kathleen D. Wilson
Carl O. Wood
Bonnie L. Woodward

1997 Retirees

Robert D. Ballard
Kenneth Burrhus
Alice I. (Tricca) Cafarella
Arthur Costa
Catherine H. Ferriera
Joel C. Goldman
George R. Hampson
James McCullough
Kenneth E. Prada
Jane M. Ridge
Stanley G. Rosenblad
Albert Santiago, Sr.
Clarence L. (Roy) Smith

Photos by Tom Kleindinst

Top photo: The Science Department and Center Administrators received the 1997 Penzance award for their overall exceptional performance, WHOI spirit, and contributions to the personal and professional lives of Institution staff. Roy Smith (G&G) speaks for the group with, from left, Judy Kleindinst (Biology), Larry Flick (DSL), Karin Bohr (PO), and Ann Henry (AOP&E) nearby; Susan Casso (MC&G) and Ellen Gately (MPC) were out of camera range. *Center photo:* Assistant Controller Dave Rudden receives congratulations from Director Bob Gagosian for being named recipient of the Vetlesen Award, given for a variety of exceptional contributions to the WHOI community over a long period of time. *Bottom photo:* Chris Hammond steps to the podium to accept the Linda Morse-Porteous Award for leadership, mentoring, dedication to work, and involvement in the WHOI community.

Degree Recipients

Woods Hole Oceanographic Institution Graduate Program in Oceanography/Applied Ocean Science and Engineering

Doctor of Philosophy

Amy Samuels
MS, BS, University of California, Davis
Special Field: *Biological Oceanography*
Dissertation: *A Systematic Approach to Measuring the Social Behavior of Bottlenose Dolphins*

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

Doctor of Philosophy

Max Deffenbaugh
BS, Princeton University
Special Field: *Oceanographic Engineering*
Dissertation: *Optimal Ocean Acoustic Tomography with Moving Sources*

Diane E. DiMassa
BS, SM, Massachusetts Institute of Technology
Special Field: *Oceanographic Engineering*
Dissertation: *Terrain-Relative Navigation for Autonomous Underwater Vehicles*

Henrietta N. Edmonds
BS, Yale University
Special Field: *Chemical Oceanography*
Dissertation: *Tracer Applications of Anthropogenic Iodine-129 in the North Atlantic Ocean*

Christopher A. Edwards
BS, Haverford College
Special Field: *Physical Oceanography*
Dissertation: *Dynamics of Nonlinear Cross-Equatorial Flow in the Deep Ocean*

Trym H. Eggen
BS, Norwegian Institute of Technology
Special Field: *Oceanographic Engineering*
Dissertation: *Underwater Acoustic Communication Over Doppler Spread Channels*

Deana L. Erdner
BS, Carnegie Mellon University
Special Field: *Biological Oceanography*
Dissertation: *Characterization of Ferredoxin and Flavodoxin as Molecular Indicators of Iron Limitation in Marine Eukaryotic Phytoplankton*

Orjan M. Gustafsson
BS, Slippery Rock University
Special Field: *Chemical Oceanography*
Dissertation: *Speciation and Ocean Fluxes of PAHs*

Robert H. Headrick
SM, OE, MIT/WHOI Joint Program
BS, Oklahoma State University
Special Field: *Oceanographic Engineering*
Dissertation: *Analysis of Internal Wave Induced Mode Coupling Effects on the 1995 SWARM Experiment Acoustic Transmissions*

Emilie E. Hooft
BS, University Toronto
Special Field: *Marine Geology and Geophysics*
Dissertation: *The Influence of Magma Supply and Eruptive Processes on Axial Morphology, Crustal Construction, and Magma Chambers*

Gary E. Jaroslow
BS, University of Massachusetts, Amherst
Special Field: *Marine Geology and Geophysics*
Dissertation: *A Geological Record of Oceanic Crustal Accretion and Tectonism at Slow-Spreading Ocean Ridges*

Igor V. Kamenkovich
BS, Moscow Institute of Physics, Oceanography and Technology
Special Field: *Physical Oceanography*
Dissertation: *Radiating Instability of Nonzonal Ocean Currents*

Craig V. Lewis
BS, Stanford University
Special Field: *Biological Oceanography*
Dissertation: *Biological-Physical Interactions on Georges Bank: Plankton Transport and Population Dynamics of the Ocean Quahog,* Artica Islandica

Dan Li
SM, Massachusetts Institute of Technology
BS, University of Science and Technology of China
Special Field: *Oceanographic Engineering*
Dissertation: *Modeling of Monostatic Bottom Backscattering from Three-Dimensional Volume Inhomogeneities and Comparisons with Experimental Data*

Ee Lin Lim
BA, Smith College
Special Field: *Biological Oceanography*
Dissertation: *New Insights on the Ecology of Free-Living Heterotrophic Nanoflagellates Based on the Use of Molecular Biological Approaches*

Daniel Lizarralde
MS, Texas A&M University
BS, Virginia Polytechnical Institute
Special Field: *Marine Geology and Geophysics*
Dissertation: *Crustal Structure of Rifted and Convergent Margins: The US East Coast and Aleutian Margins*

Laura S. Magde
BA/BS, University of California, Berkeley
Special Field: *Marine Geology and Geophysics*
Dissertation: *Mantle Upwelling, Melt Generation, and Magma Transport Beneath Mid-Ocean Ridges*

Archie T. Morrison III
AB, Harvard University
Special Field: *Oceanographic Engineering*
Dissertation: *Development of the BASS Rake Acoustic Current Sensor: Measuring Velocity in the Continental Shelf Wave Bottom Boundary Layer*

Paul E. Robbins
BA, Oberlin College
Special Field: *Physical Oceanography*
Dissertation: *Temporal Evolution of Tritium-^{3}He Age in the North Atlantic: Implications for Thermocline Ventilation*

Julian P. Sachs
BA, Williams College
Special Field: *Chemical Oceanography*
Dissertation: *Nitrogen Isotope Ratios in Chlorophyll and the Origin of Eastern Mediterranean Sapropels*

Daniel M. Sigman
BS, Stanford University
Special Field: *Marine Geology and Geophysics*
Dissertation: *The Role of Biological Production in Pleistocene Atmospheric CO_2 Variations and the Nitrogen Isotope Dynamics of the Southern Ocean*

Helen F. Webb
BSc, Worcester Polytech
Special Field: *Marine Geology and Geophysics*
Dissertation: *Quantitative Study of Pelagic Sedimentation in the Atlantic Basin*

Master of Science

Albert S. Fischer
BS, Massachusetts Institute of Technology
Special Field: *Physical Oceanography*
Dissertation: *Arabian Sea Mixed Layer Deepening During the Monsoon: Observations and Dynamics*

Jason I. Gobat
BS/BA, University of California, San Diego
Special Field: *Applied Ocean Science and Engineering*
Dissertation: *Reducing Mechanical and Flow-Induced Noise in the Surface Suspended Acoustic Receiver*

Stephanie A. Harrington
BS, University Washington
Special Field: *Physical Oceanography*
Dissertation: *Waves Trapped to Mid-Ocean Ridges*

Phillip J. LeBas
BS, Auburn University
Special Field: *Oceanographic Engineering*
Dissertation: *Maximizing AUV Slow Speed Control*

Sean P. McKenna
BS, Rensselaer Polytechnic Institute,
Special Field: *Oceanographic Engineering*
Dissertation: *The Influence of Surface Films on Interfacial Flow*

Vladimir I. Osychny
MS, Moscow State University
Special Field: *Physical Oceanography*
Dissertation: *Influence of Bottom Topography on Cross-Shelf Circulation Forced by Time Dependent Wind*

Dana R. Stuart
BS, University of Michigan
Special Field: *Marine Geology and Geophysics*
Dissertation: *Deciphering Isotopic Signals for Monsoon-induced Upwelling in Foraminifera from the Western Arabian Sea Sediment Trap*

Alvin E. Tarrell
BS, University of Nebraska, Lincoln
Special Field: *Oceanographic Engineering*
Dissertation: *A Field Investigation of Diffusion within a Submerged Plant Canopy*

Master of Science in Oceanography

Kwok-Lin Lee
BS, Chinese Culture University
Special Field: *Marine Geology and Geophysics*
Dissertation: *Petrological and Geochemical Studies of an Abyssal Peridotite from the Atlantis II Fracture Zone*

MIT/WHOI Joint Program 1997-1998 Fall Term

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

Rachel G. Adams
University of Michigan

Jess F. Adkins
Haverford College

Lihini I. Aluwihare
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Kyle M. Becker
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Pennsylvania State University, MS

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University of British Columbia, Vancouver, MS

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University of Massachusetts, Dartmouth

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

Melissa M. Bowen
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Stanford University, MS

Patricia A. Bradshaw
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Elizabeth J. Bruce
University of Washington

Sean M. Callahan
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Susan J. Carter
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Humboldt State University, MA

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University of Missouri, MS

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Moscow Physical Technical Institute

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Williams College

Albert S. Fischer
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Stanford University, MS

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University of Alaska, MS

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Elizabeth D. Garland
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University of Calgary, Canada, ME

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James Cook University, Australia

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College of St. Catherine

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University of Georgia, MS

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Korea University, MS

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Steven R. Jayne
Massachusetts Institute of Technology

Brenda A. Jensen
Eckerd College

Gwenaelle C. Jeunhomme
École Nationale Superieure de Techniques Avancées, France

Markus Jochum
Universitat Des Saarlandes, Germany

Kelsey A. Jordahl
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Tel-Aviv University, Israel, MS

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Timothy C. Kenna
Vassar College

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Massachusetts Institute of Technology, SM

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Rensselaer Polytechnic Institute

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University of Tokyo, MSc

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Kirsten L. Laarkamp
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Bowdoin College

Thomas Marchitto
Yale University

Michiko J. Martin
US Naval Academy
Troy State University, MSEd

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University of Waterloo

Sean P. McKenna
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Elizabeth C. Minor
College of William & Mary

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Ohio Wesleyan University

Marjorie F. Oleksiak
Massachusetts Institute of Technolgy

Payal P. Parekh
University of Michigan

James W. Partan
University of Cambridge, UK

Yale J. Passamaneck
University of California, Santa Cruz

Ann Pearson
Oberlin College

Nicole Poulton
Virginia Polytechnic Institute

Francois W. Primeau
University of Waterloo
University of Alberta, Canada, MSc

James M. Pringle
Dartmouth College

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

Charles E. Rawson
US Coast Guard Academy

D. Benjamin Reeder
Clemson University

Matthew K. Reuer
Carleton College

Bonnie J. Ripley
Occidental College

Gabrielle Rocap
Massachusetts Institute of Technology
Massachusetts Institute of Technology, SM

Sarah L. Russell
Pomona College

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

Alberto E. Saal
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Universidad National de Cordoba, Spain, Ph.D.

Makoto Saito
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Mary Ann Schlegel
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University of Vermont, Burlington, MA

Jennifer J. Schlezinger
Boston College

Mario R. Sengco
Long Island University, Southampton

William J. Shaw
Princeton University

Li Shu
The Cooper Union
The Cooper Union, ME

Edward R. Snow
Cornell University
MIT/WHOI Joint Program, SM

Mikhail A. Solovev
Moscow State University

Brian J. Sperry
University of Iowa

Louis C. St. Laurent
University of Rhode Island

Miles A. Sundermeyer
University of California, Santa Cruz

Nicole M. Suoja
Washington State University

Gaspar Taroncher Oldenburg
Universidad Autonoma Madrid, Spain

Alexandra H. Techet
Princeton University

Rebecca E. Thomas
Duke University

John D. Tolli
San Diego State University

Peter A. Traykovski
Duke University

Carlos H. Trevino
Instituto Technologico y de Estudios Superiores de Monterrey, Mexico

Caroline B. Tuit
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Qiang Wang
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Caixia Wang
Ocean University of Qingdao, China
Ocean University of Qingdao, China, MS

Richard M. Wardle
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Joseph D. Warren
Harvey Mudd College

Stephanie L. Watwood
University of Nebraska, Lincoln

Judith R. Wells
University of Massachusetts, Boston
University of California, Berkeley, MCP

Sandra R. Werner
Dartmouth College
Technical University of Aachen, Germany, MS
MIT/WHOI Joint Program, SM

Sheri N. White
Purdue University

Joanna Y. Wilson
McMaster University, Canada
University of Victoria, Canada, MS

Jonathan D. Woodruff
Tufts University

Fellows, Students & Visitors

Kevin Xu
Harbin Shipbuilding Engineering Institute, Peoples Republic of China
Chinese Academy of Sciences, Peoples Republic of China, MS

Wen Xu
University of Science and Technology of China, Peoples Republic of China
Institute of Acoustics, Peoples Republic of China, MS

Xiaoyun Zang
Nanjing Institute of Meteorology, Peoples Republic of China
Institute of Atmospheric Physics, Peoples Republic of China, MS

Jubao Zhang
University of Science and Technology of China, Peoples Republic of China
Chinese Academy of Science, Peoples Republic of China, MS

Yanwu Zhang
Northwestern Polytechnic University
Northwestern Polytechnic University, MS

Postdoctoral Scholar & Fellow Awards

Robyn E. Hannigan
University of Rochester
Devonshire Postdoctoral Scholar

Kai-Uwe Hinrichs
University of Oldenberg
Deutsche Forschungsgemeinschaft Postdoctoral Fellow

Matthew G. Jull
McGill University, Canada
Natural Sciences and Engineering Research Council Postdoctoral Fellow

Raquel Olguin Kelly-Jaakkola
Massachusetts Institute of Technology
National Science Foundation Minority Postdoctoral Fellow

James Leichter
Stanford University
Exxon Foundation Postdoctoral Scholar

Thomas McCollom
Washington University, St. Louis
National Science Foundation Postdoctoral Fellow

Anna Metaxas
Dalhousie University
Doherty Foundation Postdoctoral Scholar

Silvio C. Pantoja
State University of New York at Stony Brook
J. Seward Johnson Postdoctoral Scholar

Mircea Podar
University of Texas
Townsend Postdoctoral Scholar

Wade H. Powell
Emory University
Donaldson Foundation and National Institutes of Health Marine Toxicology Postdoctoral Fellow

Christopher Reddy
University of Rhode Island
J. Seward Johnson Postdoctoral Scholar

Peter E. Sauer
University of Colorado
UCAR and NOAA Climate & Global Change Postdoctoral Fellow

Alberto Scotti
Johns Hopkins University
J. Seward Johnson Postdoctoral Scholar

Anne F. Sell
University of Technology, Germany
German Academic Exchange Service and Seaver Foundation Postdoctoral Fellow

Christopher Sommerfield
State University of New York at Stony Brook
U.S. Geological Survey-WHOI Postdoctoral Scholar

Brian West
University Washington
Doherty Foundation Postdoctoral Scholar

Jonathan J. Wylie
King's College, UK
Devonshire Postdoctoral Scholar

Wenlu Zhu
State University of New York at Stony Brook
J. Seward Johnson Postdoctoral Scholar

Summer Student Fellows

Kristen B. Averyt
University of Miami

Amanda Leveau Babson
Carleton College

Jessica Leslie Bullen
Earlham College

Eleanor D. Carter
Amherst College

Robert R. Dunn
Kalamazoo College

Erica Louise Estrada
University of Texas, El Paso

Lindsey Catherine Fratessa
California Polytechnic Institute

James Campbell Kinsey
State University of New York at Stony Brook

Charles Barry Labbe
Bridgewater State College

Matthew Christopher Makowski
State University of New York at Binghamton

Kerrianne Mello
Anna Maria College

Jennifer Lynn Mercer
Black Hills State University

Reina Nakamura
John Hopkins University

Johnathan B. Pompa
Carnegie Mellon University

Christian Perry Ridley
Long Island University

Fabiola Vania Rivas
Lafayette College

Amanda Gail Searby
École Normale Superieure, France

Andrew C. Seitz
Cornell University

Eric C. Smail
Albion College

William David Struntz
Pacific Union College

Kimberly Irene Tugend
University of South Carolina

Eric Daniel Tytell
University of North Carolina

Karina Zavala
Northern Arizona University

Minority Trainees

Sharat Gadde
Yale University

Sharon Denise Perez-Suarez
University of Puerto Rico

Leigh Gabriela Torres
American University

Erica S Westcott
Clark Atlanta University

Geophysical Fluid Dynamics Summer Seminar Fellows

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University of Cambridge, UK

Jon Xinzhong Chen
Columbia University

Keir Colbo
University of Victoria, Canada

Christopher P. Hills
University of Cambridge, UK

Katsurou Katsumata
University of Tokyo, Japan

Allen C. Kuo
Columbia University

Jeffrey D. Parsons
University of Illinois

Jurgen Theiss
University of Cambridge, UK

Mary-Louise Timmermans
University of Cambridge,UK

Geophysical Fluid Dynamics Participants

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Stevens Institute of Technology

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University of California, San Diego

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Moscow Institute of Physics and Technology, Russia

Karin M. Borenas
Goteborg University, Sweden

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Eric Chassignet
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Paul J. Dellar
University of Cambridge, UK

Alexey V. Fedorov
University of California, San Diego

Glenn Flierl
Massachusetts Institute of Technology

Rupert Ford
Imperial College, UK

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Australian National University, Australia

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WHOI

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Florida State University

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University College, UK

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University of Southampton, UK

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Massachusetts Institute of Technology

Stephen Meacham
Florida State University

Philip J. Morrison
University of Texas at Austin

Photos by Shelley Lauzon

Bottom photo: Director Bob Gagosian conducts a raffle for several slots available to employees for a late May 1997 mission demo and transit cruise aboard *Atlantis*. *Top Photo:* At the rail as *Atlantis* leaves Woods Hole on the late May voyage are, from left, Kevin Kay (ship's crew), Ed Dow (raffle winner), Ken Doherty (*Alvin* group), Sue Vaughn and Pam Goulart (raffle winners), Betsey Doherty (*Alvin* group), and Karin Bohr (raffle winner).

David Muraki
New York University

Doron Nof
Florida State University

Anatoly Odulo
Applied Science Associates, Inc.

Daniel R. Ohlsen
Colorado Research Associates

Matheos P. Papadakis
University of Miami

Claudia Pasquero
University of Torino, Italy

Joseph Pedlosky
WHOI

Lawrence J. Pratt
WHOI

Antonello Provenzale
University of Torino, Italy

Audrey M. Rogerson
WHOI

Claes G. Rooth
University of Miami

Richard L. Salmon
University of California, San Diego

Roger M. Samelson
WHOI

Vitali Sheremet
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Harper Simmons
Florida State University

David Smeed
University of Southampton, UK

Ronald B. Smith
Yale University

Edward A. Spiegel
Columbia University

James Stephens
University of Reading, UK

Melvin Stern
Florida State University

Louis Tao
Columbia University

Jean-Luc Thiffeault
University of Texas

George Veronis
Yale University

John A. Whitehead
WHOI

H. Burr Steinbach Visiting Scholars

Antonio Busalacchi
NASA Goddard Space Flight Center

Michael Goulding
Rainforest Alliance's Amazon Rivers Program

Lawrence Mayer
University of Maine

Richard Peltier
University of Toronto, Canada

Steven Vogel
Duke University

Patricia Wiberg
University of Virginia

Guest Students

Christon Achong
State University of New York at Albany

Jennifer E. Ahern
Brown University

Regina Asmutis
Bridgewater State College

Ralf Bachmayer
The Johns Hopkins University

Andrew H. Barclay
University of Oregon

Kevin S. Blake
University of Rhode Island

Shari Lee Boibeaux
Cornell University

Heidi J. Clark
University of Massachusetts, Amherst

Adam Cox
Duke University

Barry J. Doust
University of Buffalo

Sarah Foster
Dalhousie University

Daniel G. Frisk
Massachusetts Institute of Technology

Jessica Goveia
Union College

Kelly Hike
Colby College

Peter Hlavaty
Lafayette College

Karine Houel
France

Heather Hunt
University of Alaska

Stephanie A. Innis
Purdue University

Nicolas Karr
France

Mai Huynh Kieu
France

Jessica Kleiss
Massachusetts Institute of Technology

Hannah Agnes Knorr
Freie Iniversity Berlin, Germany

Kara Kuzirian
University of New Hampshire

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Marianopolis College

Rebecca J. Latter
University of Southampton

Rebecca Lawrence
Trinity College

Johannes Loschnigg
University of Colorado

Laurence Alton Lougee
Gettysburg College

Julie Lovell
Colby College

Heather Macrellis
Eckerd College

Lisa M Max
Bowdoin College

Kevin McKenney
Massachusetts Institute of Technology

Molly McLellan
Colby College

Mausmi Mehta

Jennifer L. Miksis
Harvard Radcliffe College

Michael Stephen Morss
Stonehill College

Akiko Okusu
Harvard University

James W. Partan
Williams College

Sylvain Pinchat
France

Mark P. Rasmussen
Boston College

Jonathan Rechner
Bowdoin College

Susan Reed
Florida Atlantic University

Simone Reto
University of Genova, Italy

Kamran Sahami
San Diego State University

Jon W. Schuck

Margo Schulze
University of Massachusetts

Keston Smith
Temple University

Rebecca A. Smyth
University Massachusetts, Boston

Victoria Turner
University of Liverpool, England

Stefanie Suzanne Valentini
Boston University

Jennifer Villinski
Rice University

Benjamin Webster
Bates College

Sarah Whiting
Wesleyan University

Pamela M. Willis
University of Victoria, Canada

Oliver Woodhouse
University of Southampton, England

Lori Ziolkowski
University of Waterloo

Financial Statements

During 1997 the Woods Hole Oceanographic Institution continued to build on the financial strength and stability that characterized the previous two years. The financial performance of the Institution is strong as it increased the substantial unrestricted surplus recorded in 1996, reversed the decline in federal support for research that occurred in 1996, and improved an already well-reserved and conservative balance sheet. Although the negative expectations of government-sponsored research support have been replaced by cautious optimism, the Institution does not expect growth in government support and, accordingly, will continue aggressive pursuit of nontraditional sources of income.

The Institution's impressive unrestricted surplus was substantially the result of the generous gift of the Crawford property in Cotuit and the need for only 25 percent of the amount budgeted for bridge support for scientists between grants. During 1997 the Institution maintained its healthy cash position, remained debt free, experienced little staff turnover, and made several important new hires.

The Institution once again benefited from strong financial markets, growing the endowment 16 percent, net of distributions, and ending 1997 with a market value of $216 million as compared to $189 million in 1996. In addition, the retirement trust assets, which are invested along with the endowment, continued to grow in excess of liabilities. The health of the retirement trust has allowed WHOI to suspend contributions, and a detailed actuarial analysis, completed recently and covering two decades into the future, shows that the Institution will need to make contributions to the plan only under the most adverse financial circumstances.

During 1997 the Investment Committee and Retirement Trust closely monitored investment performance and revised the Institution's endowment and retirement trust asset allocation. As a result of the committee's efforts, assets were removed from sub par performing managers between September 1997 and April 1998 and placed with managers who were uniquely distinguished by their consistent performance. The excellent performance of the endowment fund has caused the distribution formula to dip below the minimums and, as a result, the Finance and Budget Committee commenced discussions on methods of increasing the amount of endowment support to the Institution.

Government-sponsored research revenue was strong for the entire year, finishing at 109 percent of budget. Sponsored research continues to be the primary source of Institution revenue, comprising 84 percent of total operating revenues (see Table 1 for an overview of Institution sources of research revenue).

The Institution's labor bases, through which fringe benefits and overhead are recovered, finished the year ahead of budget, which resulted in over-recovery of overhead, a very positive result. Anticipating this, management changed the capitalization policy during the year and took the opportunity to write off all assets on the books acquired for less than $5,000 and to purchase new administrative computers. This allowed the

Institution to absorb comfortably what would have been, in another year, a large budget consideration and to retire a large number of older computers that were not year 2000 compatible. The Institution continues to remain in full compliance with all federal regulations, and in 1997, for the third consecutive year, all government audits were current.

In 1997, gifts and grants from private sources totaled $8.4 million, compared to $8.3 million in 1996 and $6.4 million in 1995. Outstanding pledges at the end of 1997 were $3.8 million, as compared to $6.4 million in 1996 and $4.7 million in 1995. The decline reflects the conclusion of the capital campaign and the satisfaction of pledges made during that campaign.

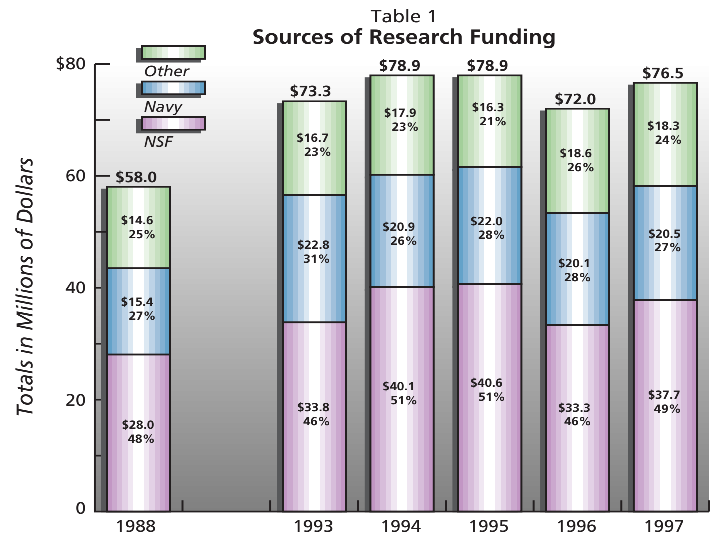
The Institution has begun to make substantial and groundbreaking progress on its financial accounting systems. Not only is the Bi-Tech administrative accounting module successfully operating, but WHOI has developed a Web-based decision support system around Bi-Tech that is efficient, comprehensive, and flexible. The administrative computing group is now fully staffed and in the process of implementing, during 1998, payroll and human resources applications. The Institution has an organized approach to the year 2000 problem with all Associate Directors developing detailed implementation plans for their areas of responsibility. At this time there appears to be no obstacle to the Institution's administrative systems being fully prepared for the new millennium.

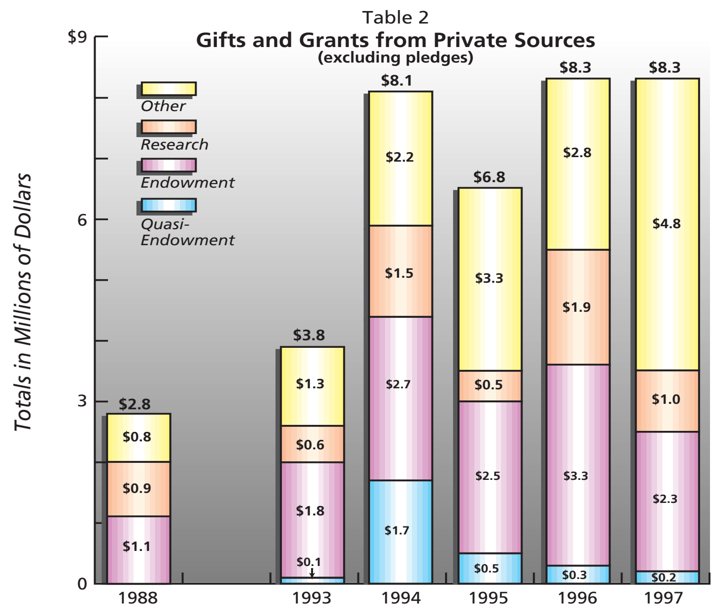
Management is continuing its efforts to follow a strategy of improving service to science while reducing administrative costs. A "Web strategy" has been adopted that seeks to provide information, transactions, and services on the Web, and there is ample evidence that the strategy is working well.

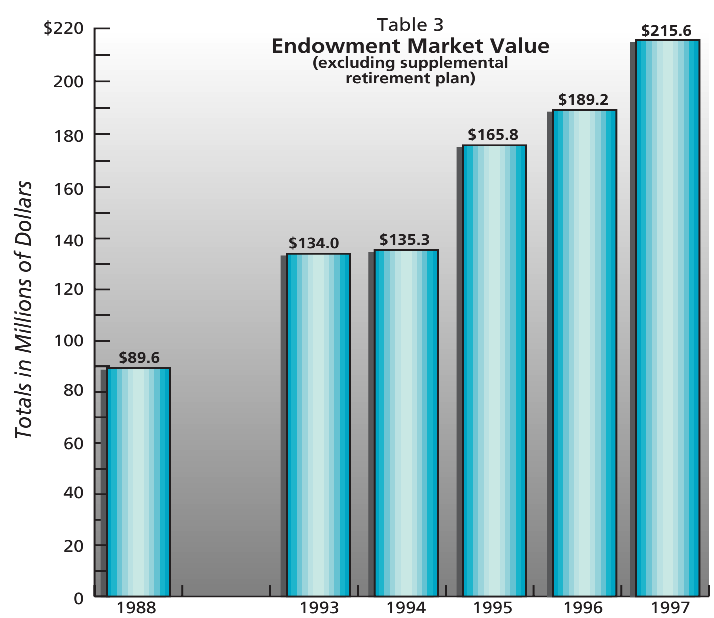
Although government support has rebounded from the declines experienced in 1996, and the predicted deep cuts anticipated are less likely to occur, the best that WHOI can hope for is that government revenues will keep pace with inflation after the year 2000. It seems certain that the Institution will need to make a substantial investment in its plant over the next 5 to 10 years and that, without increasing revenues, the cost of research projects will increase, putting WHOI at a disadvantage compared to its competitors. This means that WHOI must continue to seek other sources of funding and aggressively pursue nongovernment projects, unrestricted revenues, and endowment growth.

You are invited to review the Institution's audited financial statements and accompanying notes presented on the following pages.

—Paul Clemente
Associate Director for
Finance & Administration







Statements of Financial Position

as of December 31, 1997
(with comparative totals for 1996)

	1997	1996
Assets:		
Cash and cash equivalents:		
Operating	$ 20,754,090	$ 22,361,746
Supplemental retirement	6,197,096	-
Sponsored research prepayment pool	1,714,988	5,015,903
Endowment	12,751,386	10,946,749
	41,417,560	38,324,398
Accrued interest and dividends	996,267	1,390,377
Receivable for investments sold	874,541	555,073
Reimbursable costs and fees:		
Billed	2,282,264	2,546,825
Unbilled	2,123,117	2,223,422
Other receivables	408,129	653,285
Pledges receivable	3,810,977	6,371,351
Inventory	640,617	607,533
Deferred charges and prepaid expenses	172,688	745,955
Investments	207,593,039	183,713,682
Other current assets	4,359,882	1,650,872
Total current assets	264,679,081	238,782,773
Property, plant and equipment:		
Land, buildings and improvements	45,138,925	44,241,797
Vessels and dock facilities	2,860,533	2,582,769
Laboratory and other equipment	7,511,279	9,821,022
Work in process	59,868	117,447
	55,570,605	56,763,035
Accumulated depreciation	(29,555,091)	(30,062,749)
Net property, plant and equipment	26,015,514	26,700,286
Remainder trusts	1,175,091	1,193,720
Total assets	$291,869,686	$266,676,779
Liabilities:		
Accounts payable and other liabilities	$ 10,255,750	$ 8,957,647
Accrued payroll and related liabilities	4,898,325	4,589,116
Payable for investments purchased	1,023,779	957,743
Accrued supplemental retirement benefits	6,197,096	6,060,000
Deferred revenue and refundable advances (research)	7,668,959	10,489,415
Deferred fixed rate variance	1,756,612	1,717,821
Total liabilities	31,800,521	32,771,742

	Unrestricted	Temporarily Restricted	Permanently Restricted	1997	1996
Net assets:					
Undesignated	$ 2,305,172	$ 5,197,790		7,502,962	8,516,042
Designated	3,056,544			3,056,544	2,704,519
Plant and facilities	30,801,028	2,160		30,803,188	30,555,386
Education		3,176,835		3,176,835	2,905,450
Endowment and similar funds	56,463,024	129,829,168	$29,237,444	215,529,636	189,223,640
Total net assets	$92,625,768	$138,205,953	$29,237,444	260,069,165	233,905,037
Total liabilities and net assets				$291,869,686	$266,676,779

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

Statements of Cash Flows

for the year ended December 31, 1997
(with comparative totals for 1996)

	1997	1996
Cash flows from operating activities:		
Total change in net assets	$ 26,164,128	$ 25,702,088
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	3,623,430	2,895,184
Other nonoperating revenue	(337,505)	-
Gain on disposition of property and equipment	-	(955,000)
Net realized and unrealized (gain) loss on investments	(25,933,512)	(20,922,716)
(Increase) decrease in:		
Accrued interest and dividends	394,110	(598,338)
Reimbursable costs and fees:		
Billed	264,561	2,694,527
Unbilled	100,305	(781,202)
Other receivables	245,156	(87,592)
Pledges receivable	2,560,374	(1,624,629)
Inventories	(33,084)	22,675
Deferred charges and prepaid expenses	573,267	400,174
Deferred fixed rate variances	38,791	728,437
Other current assets	(2,709,010)	(824,672)
Remainder trusts	18,629	(242,547)
Increase (decrease) in:		
Accounts payable and other liabilities	1,298,103	449,363
Accrued payroll and related liabilities	309,209	111,017
Net payable for investments purchased	(253,432)	402,670
Deferred revenue	(2,820,456)	3,337,515
Accrued supplemental retirement benefits	137,096	579,675
Net cash provided (used) by operating activities	3,640,160	11,286,629
Cash flows from investing activities:		
Capital expenditures:		
Additions to property and equipment	(2,601,154)	(1,874,263)
Proceeds from disposals of property and equipment	-	2,455,000
Endowment:		
Proceeds from the sale of investments	174,721,760	144,129,484
Purchase of investments	(172,667,604)	(139,470,976)
Net cash provided by (used) by investing activities	(546,998)	5,239,245
Net increase (decrease) in cash and cash equivalents	3,093,162	16,525,874
Cash and cash equivalents, beginning	38,324,398	21,798,524
Cash and cash equivalents, ending	$41,417,560	$38,324,398

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

STATEMENTS OF ACTIVITIES
for the year ended December 31, 1997 (with comparative totals for 1996)

	Unrestricted					
	Operating	Sponsored Research	Temporarily Restricted	Permanently Restricted	1997	1996
Operating:						
Revenues:						
Fees	$ 540,998				$ 540,998	$ 444,371
Sponsored research:						
Government		$ 64,794,094			64,794,094	60,468,082
Nongovernment		11,641,133			11,641,133	11,503,622
Sponsored research assets released to operations	76,435,227	(76,435,227)			-	-
Education:						
Tuition	2,688,826				2,688,826	2,690,773
Endowment income	2,222,688		$ 1,260,239		3,482,927	3,298,154
Sponsored research	175,466				175,466	-
Gifts and transfers	-		180,208		180,208	467,857
Education funds released from restriction	881,218		(881,218)		-	-
Investment return designated for current operations	2,263,024				2,263,024	1,816,839
Contributions and gifts	1,975,739			$ 2,287,000	4,262,739	7,334,158
Contributions and gifts released from restriction	2,573,461		(2,573,461)		-	-
Rental income	718,875				718,875	680,800
Communication and publications	180,299				180,299	201,607
Other	76,258				76,258	752,100
Total revenues	90,732,079	-	(2,014,232)	2,287,000	91,004,847	89,658,363
Expenses:						
Sponsored research:						
National Science Foundation	37,710,475				37,710,475	33,278,264
United States Navy	20,461,324				20,461,324	20,100,408
Subcontracts	6,050,770				6,050,770	5,668,390
Advanced Research Projects Agency	485,487				485,487	1,668,951
National Oceanic & Atmospheric Administration	2,585,965				2,585,965	2,068,189
Department of Energy	1,205,005				1,205,005	1,111,832
United States Geological Survey	536,324				536,324	673,226
Other	7,399,877				7,399,877	7,402,444
Education:						
Faculty expense	2,182,244				2,182,244	1,964,120
Student expense	1,748,679				1,748,679	1,199,730
Postdoctoral programs	384,319				384,319	438,081
Sponsored research	-				-	209,718
Other	596,387				596,387	980,822
Development	2,363,145				2,363,145	1,334,767
Business development	205,635				205,635	88,752
Rental expenses	431,851				431,851	382,142
Communication and publications	564,748				564,748	655,941
Unsponsored programs	1,398,379				1,398,379	1,818,358
Other expenses	2,633,221				2,633,221	2,691,031
Total expenses	88,943,835	-	-	-	88,943,835	83,735,166
Change in net assets from operating activities	1,788,244	-	(2,014,232)	2,287,000	2,061,012	5,923,197
Nonoperating income:						
Investment return in excess of amounts designated for sponsored research, education and current operations	6,186,857		17,670,616		23,857,473	19,879,667
Plant assets released from restrictions	34,207		(34,207)		-	-
Other nonoperating revenue	337,505				337,505	-
Nonoperating expenses:						
Other nonoperating expenses	91,862				91,862	100,776
Change in net assets from nonoperating activities	6,466,707	-	17,636,409	-	24,103,116	19,778,891
Total change in net assets	8,254,951		15,622,177	2,287,000	26,164,128	25,702,088
Net assets at beginning of year	84,370,817		122,583,776	26,950,444	233,905,037	208,202,949
Net assets at end of year	$ 92,625,768	-	$ 138,205,953	$ 29,237,444	$ 260,069,165	$ 233,905,037

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

To the Board of Trustees of Woods Hole Oceanographic Institution:

We have audited the accompanying statement of financial position of Woods Hole Oceanographic Institution (the "Institution") as of December 31, 1997 and the related statements of activities and cash flows for the year then ended. These financial statements are the responsibility of the Institution's management. We previously audited and reported upon the financial statements of the Institution for the year ended December 31, 1996; totals for that year are shown for comparative purposes only. Our responsibility is to express an opinion on the financial statements based on our audit.

We conducted our audit in accordance with generally accepted auditing standards. Those standards 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. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audit provides a reasonable basis for our opinion. In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of Woods Hole Oceanographic Institution as of December 31, 1997 and the changes in its net assets and its cash flows for the year then ended, in conformity with generally accepted accounting principles.

Coopers + Lybrand L.L.P.

Boston, Massachusetts
March 13, 1998

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 exempt from federal income tax as an organization described in Section 501(c)(3) of the Internal Revenue Code of 1954 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 are presented on the accrual basis of accounting and have been prepared to focus on the Institution as a whole and to present balances and transactions according to the existence or absence of donor-imposed restrictions. The presentation follows the provisions of 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 generally requires that contributions received, including unconditional promises to give, be recognized as increases in net assets in the period received at their fair values. 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 in total, but not by net asset class. The prior-year information presented does 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 organization's financial statements for the year ended December 31, 1996, 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 or the Institution's interpretation of relevant state law 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 statement of activities reports 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 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, 1997 and 1996 is $1,714,988 and $5,015,903, respectively, representing advances received from the United States Navy and other U.S. Government 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. Unrestricted investment income is recognized as revenue when earned and restricted investment income is recognized as revenue when it is expended for its stated purpose.

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 $6,945,710 and $6,394,825 for the years ending December 31, 1997 and 1996, 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 2% to 12 1/2% on buildings and improvements, 3 1/2% on vessels and dock facilities, and 20% to 33 1/3% on laboratory and other equipment. Depreciation expense on property, plant, and equipment purchased by the Institution in the amounts of $3,531,568 and $2,794,408 in 1997 and 1996, respectively, has been charged to operating activities.

Depreciation on certain government-funded facilities (the Laboratory for Marine Science and the dock facility) amounting to $91,862 and $100,776 in 1997 and 1996, respectively, has been charged to nonoperating expenses as these assets are owned by the Government. Gains on the disposal of property, plant and equipment totaled $955,000 during the year ended December 31, 1996; there were no such gains in 1997.

Use of Estimates

The preparation of the financial statements in conformity 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, 1997 and 1996, 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, 1997 presentation.

C. Investments:

The cost and market value of investments held at December 31, 1997 and 1996 are as follows:

	1997		1996	
	Cost	Market	Cost	Market
U.S. Government and government agencies	$ 13,173,280	$ 13,610,082	$ 15,871,067	$ 15,874,658
Corporate bonds	13,124,913	13,556,058	13,016,798	13,126,042
Other bonds	3,053,621	3,086,994	3,551,636	3,645,641
Equity securities & mutual funds	104,656,472	144,559,252	94,506,630	141,130,158
International equity mutual funds	9,420,852	9,549,820	5,723,594	6,384,442
Venture Capital and Investment Partnership Investments	17,843,263	21,800,471	4,093,040	3,552,741
Other	1,338,363	1,430,362	-	-
Total investments	$162,610,764	$207,593,039	$136,762,765	$183,713,682

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 $841,848 and $602,081 for the years ended December 31, 1997 and 1996, respectively, including dividends, distributions and changes in the estimated value of such investments. The following schedule summarizes the investment return and its classification in the statement of activities:

	Unrestricted	Temporarily Restricted	Permanently Restricted	1997 Total	1996 Total
Dividend and interest income	$4,876,872	$1,260,239		$6,137,111	$6,186,018
Investment management costs	(663,787)			(663,787)	(569,502)
Net realized and unrealized gains	8,262,896	17,670,616		25,933,512	20,922,716
Total return on investments	12,475,981	18,930,855		31,406,836	26,539,232
Investment return designated for:					
Sponsored research	(1,803,412)			(1,803,412)	(1,544,572)
Education	(2,222,688)	(1,260,239)		(3,482,927)	(3,298,154)
Current operations	(2,263,024)			(2,263,024)	(1,816,839)
Investment return in excess of amounts designated for sponsored research, education and current operations	$6,186,857	$17,670,616	-	$23,857,473	$19,879,667

Endowment income is allocated to each individual fund based on a per unit valuation. The value of an investment unit at December 31, 1997 and 1996 is as follows:

	1997	1996
Unit value, beginning of year	$3.3191	$3.0058
Unit value, end of year	3.6785	3.3191
Net change for the year	.3594	.3133
Investment income per unit for the year	.0918	.0906
Total return per unit	$ .4512	$ .4039

D. Pledges Receivable:

Pledges receivable consist of the following at December 31:	1997	1996
Unconditional promises expected to be collected in:		
Less than one year	$ 1,577,977	$ 2,656,945
One year to five years	2,233,000	3,714,406
	$ 3,810,977	$ 6,371,351

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, 1995	$ (989,384)
1996 indirect costs	29,882,057
1996 adjustment	(59,634)
Amounts recovered	(30,550,860)
1996 (over)/under recovery	(728,437)
Deferred Fixed Rate Variance (liability), December 31, 1996	(1,717,821)
1997 indirect costs	31,584,174
1997 adjustment	67,108
Amounts recovered	(31,690,073)
1997 (over)/under recovery	(38,791)
Deferred Fixed Rate Variance (liability), December 31, 1997	$(1,756,612)

As of December 31, 1997 the Institution has recovered a cumulative amount in excess of expended amounts of $1,756,612 which will be reflected as a reduction of future year recoveries. This amount has been reported as a liability of the Institution.

F. Retirement Plans:

The Institution maintains a noncontributory defined benefit pension plan covering substantially all employees of the Institution, and a supplemental benefit 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.

Net periodic pension cost for the two plans consists of the following for 1997:

	Benefit Plan	Supplemental Benefit Plan
Service cost	$ 2,825,980	$ 106,384
Interest cost	6,720,858	240,658
Actual return on plan assets	(20,170,912)	(234,676)
Net amortization and deferral	10,025,919	22,898
Net periodic pension (income) expense	$ (598,155)	$ 135,264

Below is a reconciliation of the funded status of the plans at December 31, 1997:

	Defined Benefit Plan	Supplemental Benefit Plan
Actuarial present value of obligation:		
Vested benefit obligations	$ (82,991,456)	$(1,725,173)
Nonvested benefits	(1,491,723)	(1,002,901)
Accumulated benefit obligation	$ (84,483,179)	$(2,728,074)
Projected benefit obligation	$(107,000,311)	$(3,576,307)
Fair value of plan assets (primarily invested in common stocks and fixed income securities)	149,537,244	-
Plan assets in excess of the projected benefit obligation	42,536,933	(3,576,307)
Unrecognized net transition (asset) obligation	(2,583,433)	514,864
Unrecognized prior service costs	3,064,309	-
Unrecognized net gain	(41,931,067)	(509,282)
(Accrued) prepaid pension cost	$ 1,086,742	$(3,570,725)

At December 31 1997, the defined benefit plan assets listed above are held in the Woods Hole Oceanographic Retirement Trust. The Institution has accrued a liability sufficient to fund future supplemental plan benefits at December 31, 1997. During 1997, the Institution transferred $6,060,000 related to the Supplemental Benefit Plan to a segregated account available to fund Supplemental Plan benefits. The assets of the Retirement Trust are comprised primarily of common stock and fixed income securities, while the Supplemental Plan is in cash equivalents.

For December 31, 1997 and 1996, the funded status was determined using a discount rate of 6.75% and 7.25%, respectively, and a rate of increase in future compensation of 4.5%, for both years. The expected return on plan assets was 9% for both years.

G. Other Post Retirement 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.

The Institution has adopted the delayed recognition method as permitted by Statement of Financial Accounting Standards No. 106, "Employer's Accounting for Postretirement Benefits Other Than Pensions." As such the Institution is amortizing the accumulated postretirement benefit over 20 years.

Net periodic postretirement benefit cost consists of the following for 1997:

Service cost	$ 366,931
Interest cost	1,288,248
Actual return on plan assets	(1,795,203)
Net amortization and deferrals	1,351,621
Net periodic postretirement benefit cost	$1,211,597

The Institution utilizes a Voluntary Employees' Beneficiary Association Trust (the "Trust") to partially fund health care benefits for future retirees. The Institution intends to contribute to the Trust an amount equal to the annual expense of the postretirement Plan. During the year ended December 31, 1997 the Institution paid $1,366,620 in retiree health benefits on behalf of the Trust.

The following table sets forth the funded status of the Plan as of December 31, 1997:

Financial status of postretirement plan:	
Accumulated postretirement benefit obligation:	
Retirees	$ (10,777,027)
Fully eligible, active plan participants	(3,455,751)
Other active plan participants	(4,442,865)
Total obligation	(18,675,643)
Plan assets at fair value	11,621,125
Unrecognized net transition obligation	12,803,242
Unrecognized prior service cost	(5,265,770)
Unrecognized loss	363,520
Prepaid postretirement benefit cost	$ 846,474

For December 31, 1997 and 1996, the funded status was determined using a discount rate of 6.75% and 7.25%, respectively. The expected long-term rate of return on plan assets used in determining the net periodic postretirement benefits cost was 8.25% in 1997. The rate of increase in the per capita costs of covered health care benefits is assumed to be 5.5% in 1997 and in future years.

If the health care cost trend rate assumptions were increased by 1%, the accumulated postretirement benefit obligation, as of December 31, 1997, would be increased by approximately $2,821,889; the effect of this change on the sum of the service cost and interest cost components of net periodic postretirement benefit cost for 1997 would be an increase of approximately $315,919.

H. 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 have settled the years through 1996. The current indirect costs recovery rates, which are fixed, include the impact of prior year settlements. While the 1997 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.

I. Implementation of SFAS 132

Effective for the fiscal year ending December 31, 1998, the Institution will be required to implement Statement for Financial Accounting Standards (SFAS) No. 132, "Employers' Disclosures about Pensions and Other Post Retirement Benefits". SFAS No. 132 revises employers' disclosures about pension and other post retirement benefit plans, but does not change the measurement or recognition provisions of previous standards which impact such plans.